An Autonomous Unmanned Aerial Vehicle (UAV) System for Ocean Hazard Recognition and Rescue: Scout and Rescue UAV Prototypes

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Engineering Goals

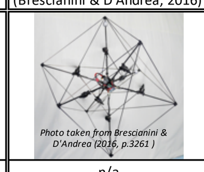
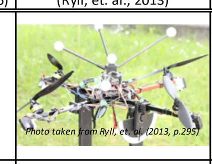
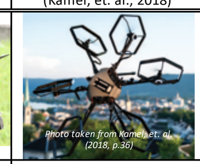
- Define lifeguard UAV design requirements.
- *Scout UAV*: Design, implement, and perform scout missions of ocean image data collection for water flow analysis.
- *Rescue UAV*: Design, fabricate, build, and implement a drone for omni-directional flight and slung-load pulling.

Project Origin

- ***Unguarded beaches*** have 5 times more drowning deaths than guarded beaches in U.S. WHO estimates 90% of drowning deaths are from low- and middle-income countries.
- ***Rip currents*** are responsible for most beach drownings at both guarded and unguarded beaches, and 80% of rescues by lifeguards are from rip currents.
- ***Current beach UAVs are operated manually.*** Early adoption at select beaches requires manual piloting and visual examination to detect threats.

Work by Others

- UAVs were introduced to beaches for rip current, victim, and predator detection, though they require manual pilot and observation.
- Optical flow and rip current analysis (Dérian & Almar, 2017; Holland, et. al., 2001, Lucas & Kanade, 1981).
- UAVs with roll or pitch tilt rotors, or omni-directional flight capability:

Citation	(Brescianini & D'Andrea, 2016)	(Ryll, et. al., 2013)	(Kamel, et. al., 2018)	(Allenspach, et. al., 2020)
Photo	 Photo taken from Brescianini & D'Andrea (2016, p.3261)	 Photo taken from Ryll, et. al. (2013, p.295)	 Photo taken from Kamel, et. al. (2018, p.36)	 Photo taken from Allenspach, et. al. (2020, p.11)
Rotor tilt	n/a	Roll	Roll	Roll
Maxium rotor pitch angle	n/a	n/a	n/a	n/a
Coaxial	No	No	No	Yes

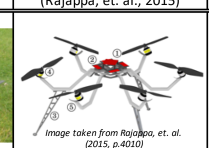
Citation	(Segui-Gasco, et. al., 2013)	(Rajappa, et. al., 2015)	(Junaid, et. al. 2018)
Photo	 Photo taken from Segui-Gasco, et. al. (2013, p.375)	 Image taken from Rajappa, et. al. (2015, p.4010)	 Image taken from Junaid, et. al. (2018, p.3)
Rotor tilt	Roll and pitch	Roll and pitch	Roll and pitch
Maxium rotor pitch angle	<20	<40	<20
Coaxial	No	No	No

Table created by the author

Methods: Plan and Requirements

Lifeguard UAV Development Phases

Phase	Description	Location	Duration
Pre Phase	Preliminary research	Home, IEEE	June 2022 - May 2023
Phase I	Design and certification	Home	June 2023 - Dec 2023
Phase II	Prototyping fabrication and SW development	Home (Garage)	Aug 2023 - Feb 2024
Phase III	Pilot tests and revisions	Backyard Tennis courts Del Mar Beach	Oct 2023 - current
(Phase IV)	(Scale up manufacturing)	*(Out of the current project scope)*	

Table created by the author

- ***Scout UAV*** **&** ***rescue UAV***: Lifeguard observation and rescue missions have distinctly separate operational priorities and functional differences; separate UAV design functionalities are required for scout observation and rescue missions.
- ***Scout UAVs*** operate continuously with spatial and temporal overlap for ocean patrol.
- ***Rescue UAVs*** are activated on demand to perform rescue missions with physical capacity.
- ***A lifeguard UAV fleet*** is composed of multiple scout and rescue UAVs.

Lifeguard UAV requirements

	Plan	
Requirement	Scout UAV	Rescue UAV
AI capability	On-board mission controller	
Precise control	Multiple IMUs and GPSs in FC	
Flight duration	High-density, large-capacity Li-Ion	High current LiPo
Reliable communication	Wide-range and redundant radio links	
Multiple camera	Camera gimbal and fixed mount camera	
Payload	Up to 3Kg	Up to 20Kg
Thrust for payload	>6x9.8N	>40x9.8N
Omni-directional flight	-	Dual-axis tilt rotor
No orientation singularity	-	Extended and symmetric pitch rotor tilt
Carry lifesaving tool	-	Capable
Pull victim to safety	-	Tilt rotor and multiple arms for thrust
Reliable thrust	-	Coaxial hexacopter for redundancy
Transportation	Fit in passenger vehicle	Fold to fit in passenger vehicles

Table created by the author

Methods: *Scout UAV*: Design and Build

- Design requirements:
- ***AI-capability***: NVIDIA JETSON Nano mission controller
- ***Reliable link***: Triple wide-range telemetry, IP network, and RC radios
- ***Flight duration***: Higher energy density and large-capacity 4S Li-Ion battery
- ***Thrust***: 2317 actuator and 11-inch propeller for 6.7×9.8N total thrust for additional payload and wind resistance
- Regulation compliance

Scout UAV system diagram and build photos

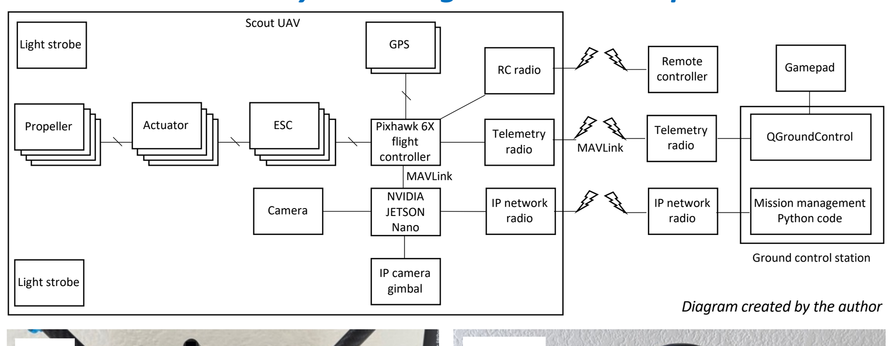
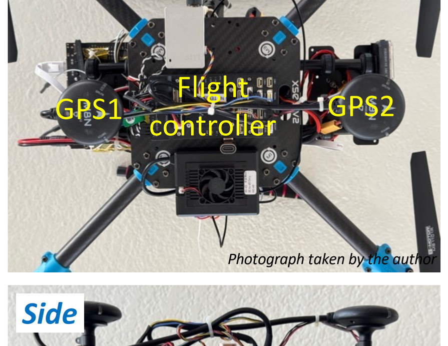
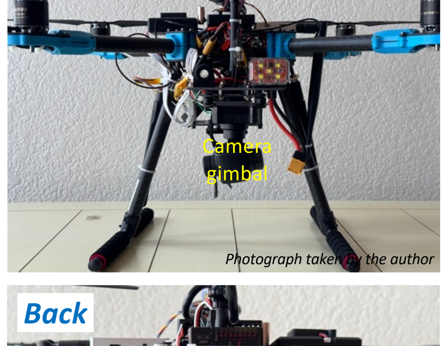


Diagram created by the author





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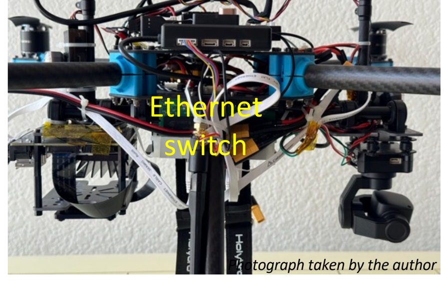


Photograph taken by the author

Pre-flight setup

Photograph taken by the designated supervisor

Take off

Photograph taken by the author

Methods: *Scout UAV*: Scout Missions

- Ocean image data collection scout missions at Del Mar Beach in October – December 2023
  - *9* scout missions
  - *11.8k* ocean images
  - *13.4km* shoreline mileage
  - *The King Tides* on 12/25
- Frame rates: 1, 5, and 10 frames per second
- Altitude: 50 and 100m, below FAA restriction (121m)
- Flight speed: 5m/s
- FAA UAV pilot certification **RECF29679944364**, UAV registration **FA3HRKM494**. FCC amateur Technician license as **N6SEA** for privileged frequency bands.

NOAA tide chart

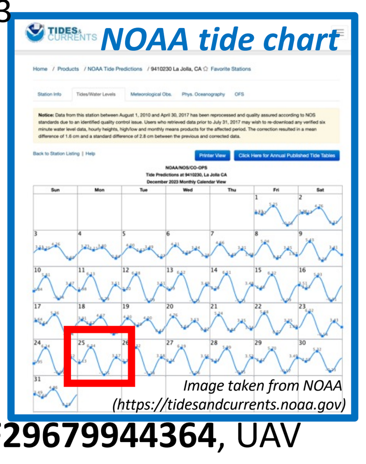


Image taken from NOAA (https://tidesandcurrents.noaa.gov)

Scout flight missions at Del Mar Beach

Flight #	Date	Time	Duration	Distance (km)	Altitude (m)	Take off	Frame per second	# of images	Data size (MB)
1	10/28/23	7:22	0:04:40	1.03	50	18th St.	1	0	0
2	10/28/23	7:39	0:04:48	1.04	50	18th St.	1	289	99.3
3	11/17/23	16:33	0:03:22	0.53	100	18th St.	1	88	27.9
4	11/17/23	16:42	0:06:45	1.52	100	18th St.	1	0	0
5	11/17/23	17:00	0:06:33	1.50	100	18th St.	1	299	58.5
6	11/22/23	8:19	0:08:38	2.09	100	27th St.	5	1950	499
7	11/22/23	9:01	0:07:27	1.75	100	18th St.	5	1660	441.5
8	12/25/23	9:43	0:08:29	2.04	100	27th St.	10	3995	2120
9	12/25/23	10:14	0:07:52	1.90	100	15th St.	10	3600	1900
Total			0:58:34	13.4				11881	5146

Table created by the author

Results: *Scout UAV*: Information-Weighted Optical Flow Analysis

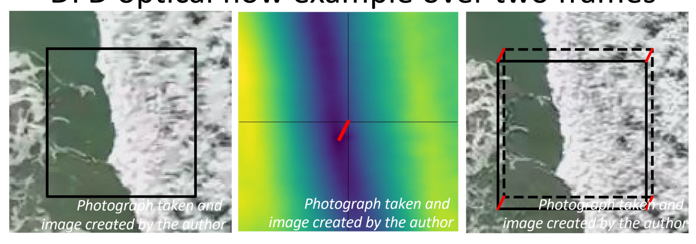
- **Finding 1 -** Conventional optical flow analyses become errant when information is scarce
  - Differential Frame Displacement (DFD)
  - Error Cross-Correlation (ECC)
  - Lucas-Kanade (LK) technique

$$\mathbf{u}_{\mathrm{DFD}} = \arg\min_{\mathbf{u}} \left\{ \int_A |\Delta I(\mathbf{x},\mathbf{u})|^2 + k \int |f_{reg}|^2 \right\}$$ (Dérian & Almar, 2017)

$$\mathbf{u}_{\mathrm{ECC}} = \arg\max_{\mathbf{u}} \left\{ 1 - \frac{\int_A |I - I(t,\mathbf{u})|}{\int_A I + I(t,\mathbf{u})} \right\}$$ (Holland, et. al., 2001)

$$\mathbf{u}_{\mathrm{LK}} = -(\mathbf{A}_P{}^T \mathbf{A}_P)^{-1} \mathbf{A}_P^T \frac{\delta \mathbf{I}_P}{\delta t}$$ (Lucas & Kanade, 1981)

- DFD optical flow example over two frames



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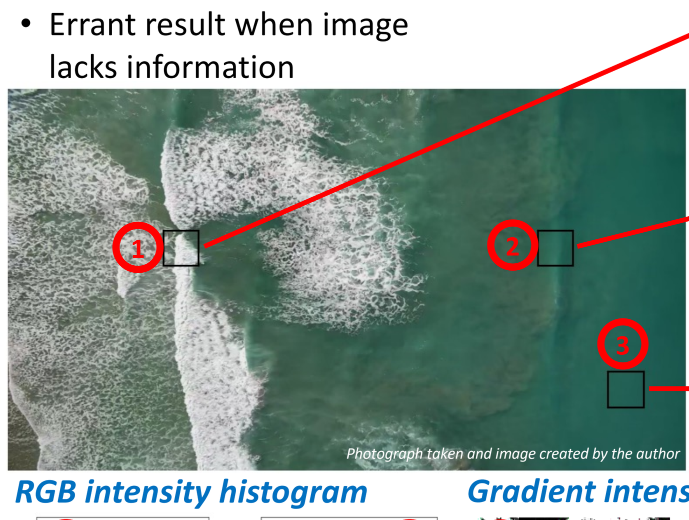
- Errant result when image lacks information



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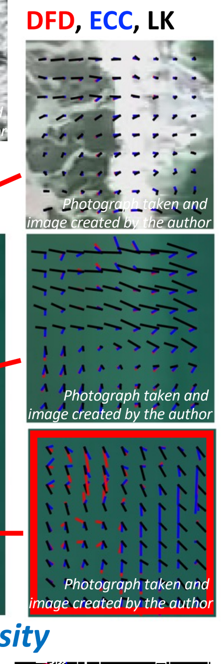
DFD, ECC, LK



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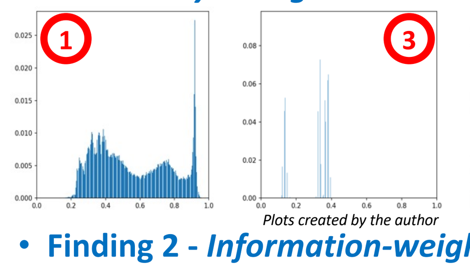
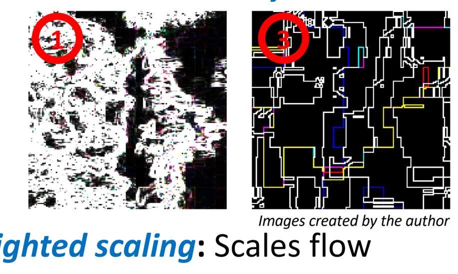
RGB intensity histogram



Plots created by the author

Gradient intensity



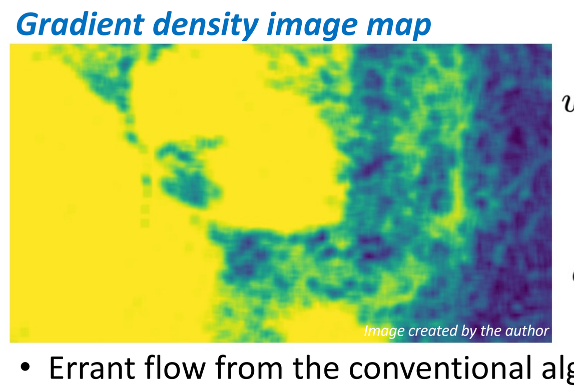
Images created by the author

- **Finding 2 -** ***Information-weighted scaling***: Scales flow estimation from information-deprived image
- **Finding 3 -** ***Gradient density***: Used as a measure of information

Information-weighted flow

$$\mathbf{u}_w(\mathbf{x}) = w_d(\mathbf{x})\bar{\mathbf{u}}(\mathbf{x})$$

Gradient density image map



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Information weight

$$w_d(\mathbf{x}) = \frac{d_{\mathrm{window}}(\mathbf{x})}{d_{\mathrm{entire\ image}}}$$

Gradient density

$$d(\mathbf{x}) = \frac{1}{A_I} \sum_{|\delta|>0} |\nabla I|$$

- Errant flow from the conventional algorithm is reduced in information-scarce areas.

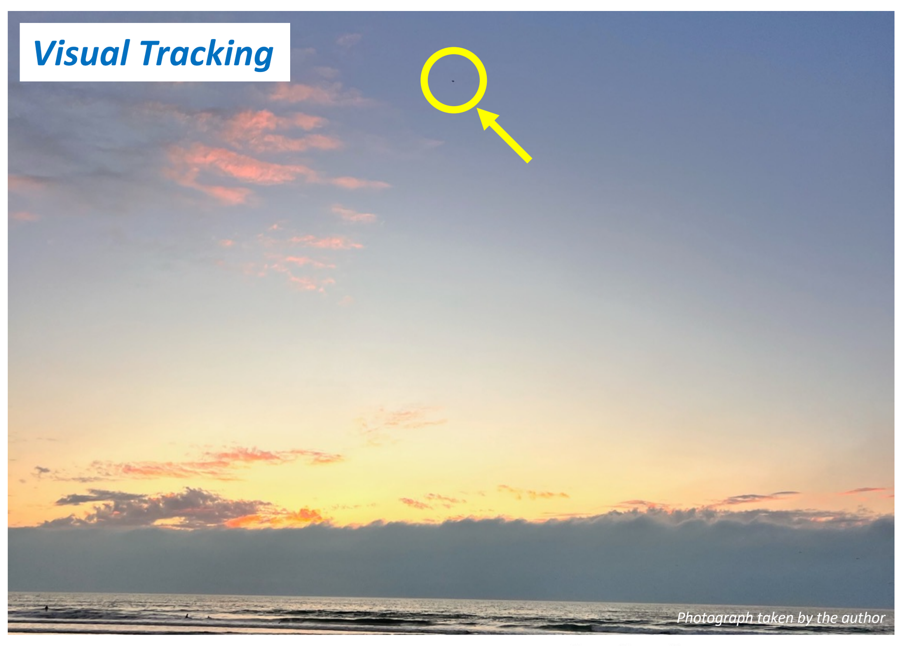
Results: *Scout UAV*: Channel Current Flow with Depth Risk Models

- **Conventional model:** Surface flow only
- **Finding 4** - Rip channel current with depth risk models
- ***Depth model***: Flow is weighted by the depth model to estimate water volume flow
- ***Depth and risk model***: Model human risk factor in addition to depth
- ***Channel flow***: Estimated from wave, channel, and time integration

Ground control station

Photograph taken by the author

Visual Tracking



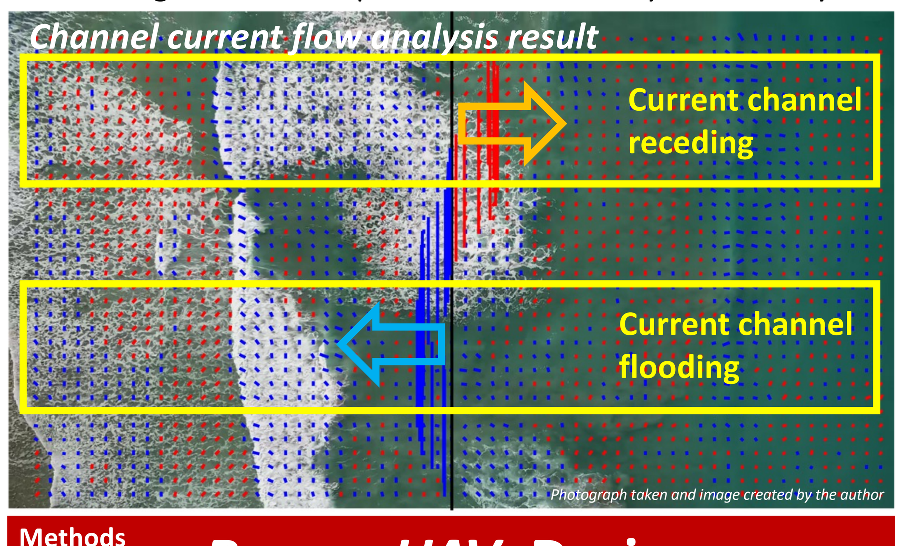
Photograph taken by the author

Channel current estimation $f_{\mathrm{flow}} = \int_T \int_C \int_W c(x) \cdot \mathbf{u}_w(x)$

Depth and risk model $c_{\mathrm{risk}}(x) = b_{\mathrm{depth\ risk}} \cdot x^2$

- **Results:** Channel current flow estimates net receding and flooding flow with depth and risk model systematically.

Channel current flow analysis result



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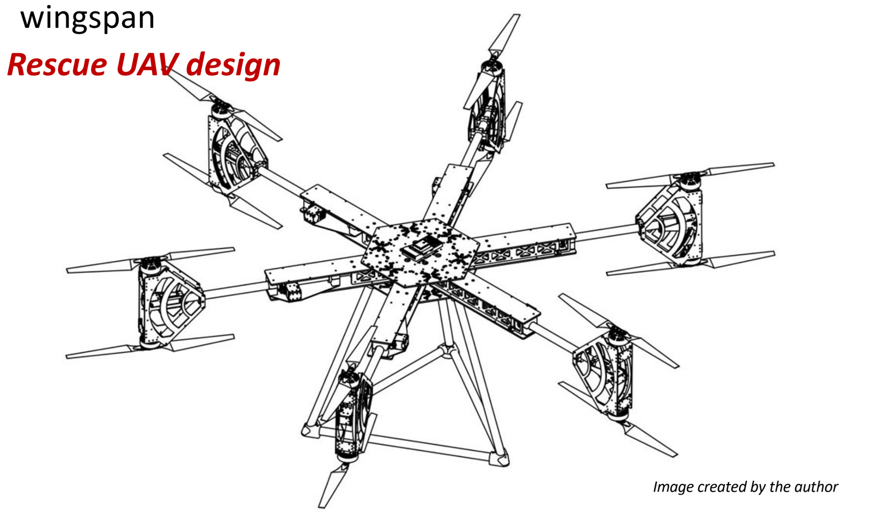
Methods: *Rescue UAV*: Design

- Design requirements:
- ***Omni-directional flight***: Extended and symmetric dual-axis tilt rotor
- ***Thrust***: 44.1×9.8N total thrust for rescue operation
- ***Redundancy***: Coaxial hexacopter with 12 actuators
- ***Transportation***: Triple folding by 45% to 1.1m from 2.0m wingspan

Rescue UAV design



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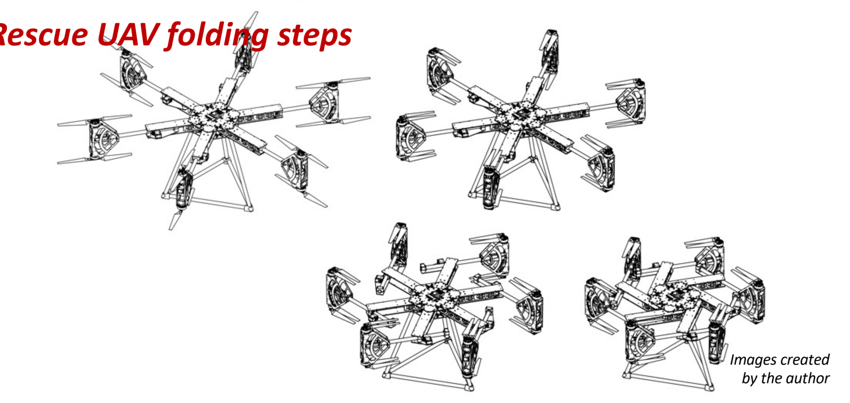
Rescue UAV folding steps



Images created by the author

Methods: *Rescue UAV*: A Novel In-Arm Pitch Axis

- ***Extended pitch tilt angle*** for stable omni-directional flight without singularity.
- ***In-arm pitch axis*** improves maximum pitch angle by 65% over conventional end-arm pitch axis.

Conventional end-arm vs. in-arm pitch axis

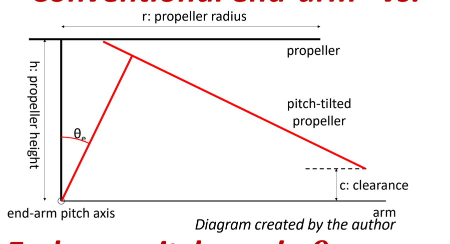


Diagram created by the author

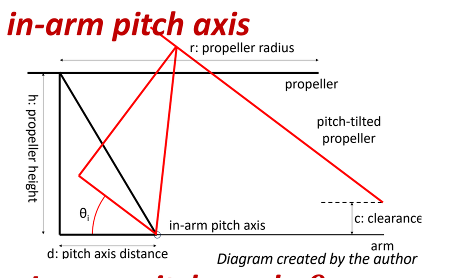


Diagram created by the author

End-arm pitch angle θ_e

$$\theta_e = \tan^{-1}\left(\frac{h}{r+c}\right)$$

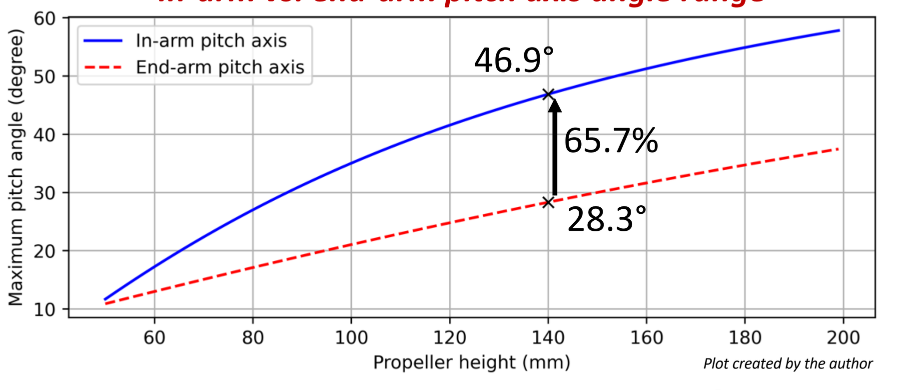
In-arm pitch angle θ_i, where $k = r - d$

$$h\cos\theta_i + d\sin\theta_i = c + r\sin\theta_i$$

$$\theta_i = \sin^{-1}\left(\frac{-k + \sqrt{c^2k^2 - (k^2+h^2)(c^2-h^2)}}{k^2+h^2}\right)$$

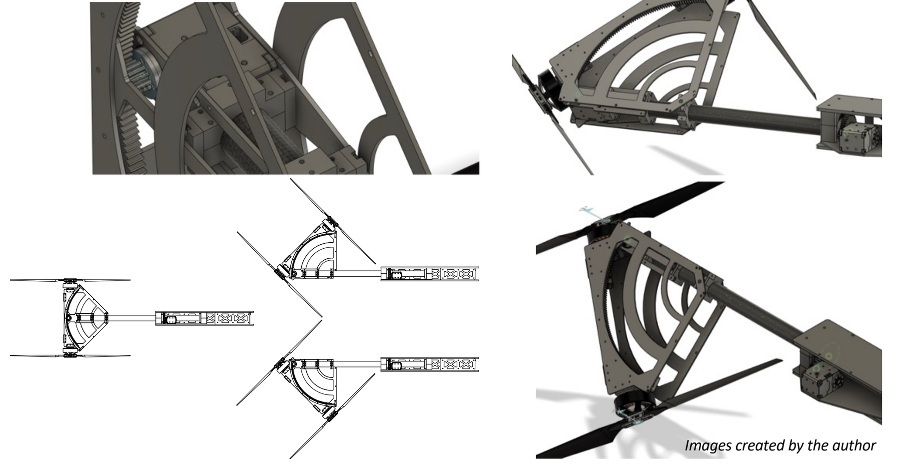
- End-arm axis maximum angle: 28.3°
- ***In-arm pitch axis*** maximum angle: ***46.9°***
- Improvement by ***65.7%***
- Propeller height = 140mm

In-arm vs. end-arm pitch axis angle range



Plot created by the author

In-arm pitch axis rotation design



Images created by the author

Methods: *Rescue UAV*: Fab and Build

- *2 and 4mm* carbon fiber boards
- *12* 5008 actuators and 457mm (18-inch) propellers
- *12* electronic speed controls
- *12* servo motors
- *75m* wiring
- *86* CNC-machined carbon fiber boards
- *320* Nylon 3D-printed custom parts
- *1,000* M2, M2.5, and M3 screws for assembly

Rescue UAV build process

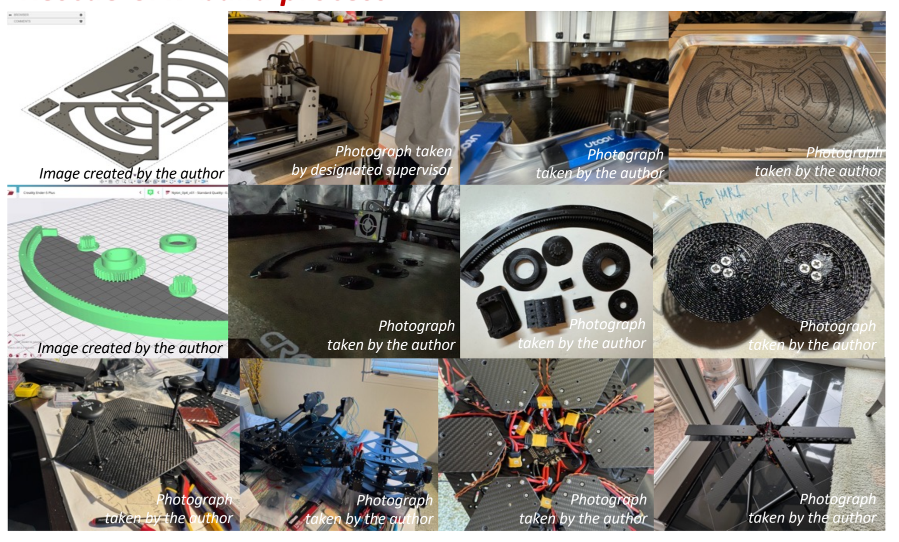
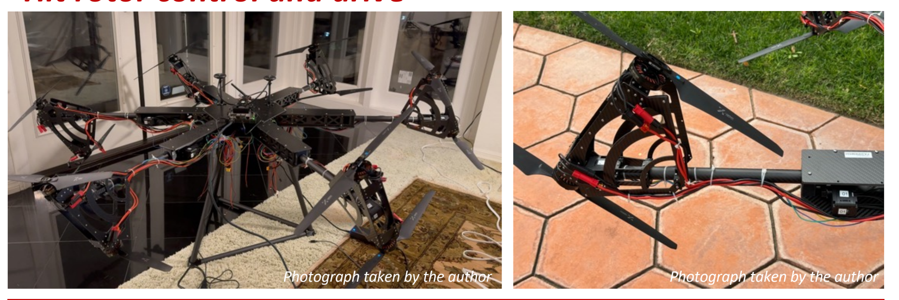


Image created by the author; Photograph taken by designated supervisor; Photograph taken by the author

Results: *Rescue UAV*: Dual-Axis Tilt Rotor Drive

- ***Mission management Python*** program commands servo motors in extended position mode.
- ***Calibrate pitch and roll*** positions at each arm.
- Target pitch and roll angles are translated to servo motor positions.
- ***Control allocation and mixing*** by mission controller and flight controller together necessary.

Tilt rotor control and drive

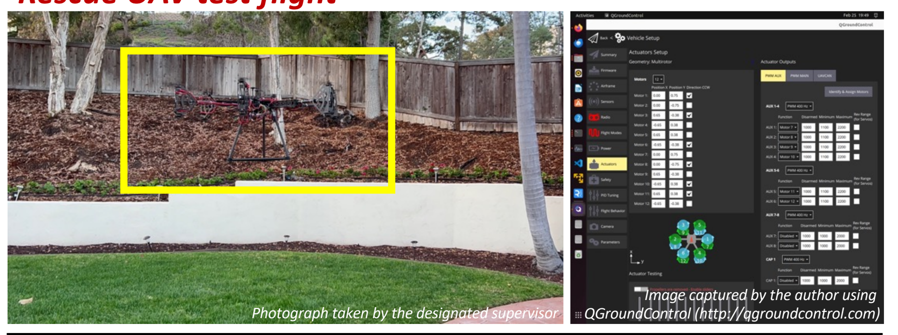


Photograph taken by the author

Results: *Rescue UAV*: Test Flights

- ***Control allocation or mixing*** is set as default coaxial hexacopter or dodecacopter at PX4 Autopilot through QGroundControl
- ***Pitch and roll*** are at neutral position
- 2x 6S LiPo battery for up to 360A current
- Test flights conducted successfully with 12.3Kg weight + 1Kg LiPo batteries

Rescue UAV test flight



Photograph taken by the designated supervisor; Image captured by the author using QGroundControl (http://qgroundcontrol.com)

Findings and Significance

- **New lifeguard UAV system was designed, developed (prototyped) and pilot-tested as follows:**

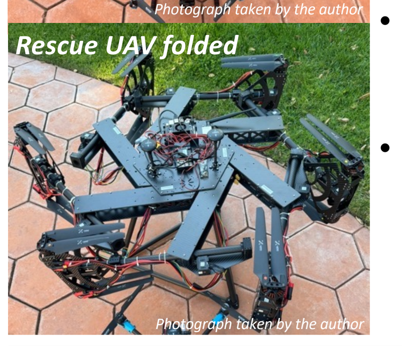
1. **Autonomous scout UAV** was built and operated
   - ✓ For threat detection, a new image analysis model with **information-weighting** for ocean water flow was built
   - ✓ A new **rip current channel analysis** was conducted and **depth and risk models** were built
2. **Autonomous rescue UAV** was built and tested
   - ✓ **A novel in-arm pitch axis** improved range by 65% with a goal for omnidirectional flight to align the center of mass and resolve slung-load problem to pull victim under dynamic environment
3. **Applications – Public Safety, Military, and Industry**
   - ✓ High-degrees-of-freedom dynamic UAV flight
   - ✓ Rescue mission under extreme condition
   - ✓ Robust and failure-resistant UAV
   - ✓ Load delivery through complex terrain
   - ✓ Remote instrumentation on infrastructure
   - ✓ Role-based UAV fleet operation

Next Steps and Conclusion

Scout and Rescue UAVs

Photograph taken by the author

Rescue UAV folded



Photograph taken by the author

- ***The scout UAV***: Implement real-time image processing and rip current detection with mission controller.
- ***The rescue UAV***: Solve Newton-Euler equations of motion for a rigid body and the slung load problem.
- ***Autonomous UAVs*** reduce socioeconomic mortality and ocean safety disparity.
- The project advances current lifeguard practices with improved coverage, accuracy, and speed at a lower cost while demonstrating feasibility.

Key References

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