Technical Overview of the Development of Autonomous Submarines Lanturn and Donphan

Ricardo Medina(CS, Team Captain), Aren Petrossian (ME, Team Co-Captain), Eric Anthony (ME), Saul Loza (ME), Heriberto Gonzalez (CS)

1. ABSTRACT

The previous designs of our submarine robots are carefully reviewed, and significant improvements are made to the two vehicles, LANTURN and DONPHAN. (1) First, modifications for heat dissipation are made to ensure the electronics always work in a preferred temperature environment. Heating has always been a critical issue for submarine robots with electronics of high power consumption enclosed in a confined space. This improvement was achieved through 1) designing a metal hull with an effective heat condition mechanism to direct heat from the heating sources to the metal hull, and 2) regulating heat generation through optimizing the operation of calculation extensive tasks. (2) Second, the software team creates an architecture that supports easy expansion depending on the tasks outlined by the competition. (3) Third, since the time available at the competition is limited for the team to collect a large enough dataset for training of machine learning algorithms, the team assembled a list of methods for generating simulated images for training. (4) Modifications were made to the frame allowing subsystems to be mounted on various parts of the AUV as necessary. Simulations and experiments show that these design creativities meet our expectations, which will help the team stay in a competitive position for this year's competition.

2. COMPETITION STRATEGY

Our strategy for the year is reusability and modularity. The mechanical design for CSULA's LANTURN submarine was focused on ease of manufacture and maintenance. The design allows for modular systems to be designed and mounted for future years. Special consideration was taken to ensure that overheating would not be an issue. In addition our software approach was restructured. Focus was placed on separating code to individual modules dedicated to a specific task. These modules are able to be created and tested separately allowing testing on hardware to follow a more Agile methodology. This will also allow the reuse of functioning code where applicable, and modification to existing code to account for changes in the yearly competition. The computer vision portion of the software was of particular note. The competition requires heavy use of object recognition and our goal was to have a functioning system. Overall this strategy should allow us to build on our work for future competitions, and allow us to further add required complexity to complete the task set forward by the competition.

3. DESIGN CREATIVITY

A. MECHANICAL

Key design features of LANTURN are a box-shaped hull with a removable electronics shelving unit and a frame with slotted mounting points for modular mounting of subassemblies.

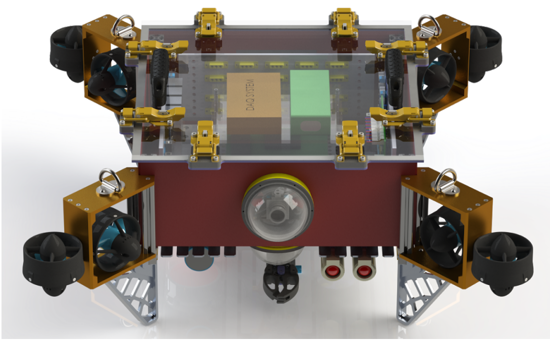


Figure 1. CSULA's LANTURN Vehicle

LANTURN's hull primary structure is formed by TIG welded sheets of AL 6061-T6. The lid is made of transparent acrylic, and seals to the hull primary structure through a peripheral nitrile gasket compressed by latches. LANTURN is outfitted with forward and downward facing cameras and features a rear connector plate populated with a standardized set of Seacon connectors. The electronics shelving unit is made of acrylic sheets laser cut to shape/size with equally spaced mounting holes that span each sheet.

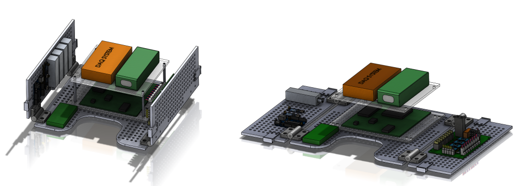


Figure 2. Removable electronics shelving

An internal connector plate and connectorized electronics allow the shelving unit to be unplugged and removed from the hull. 90 degree snapping latches allow the shelves to be laid flat outside of the sub for easy maintenance and troubleshooting.

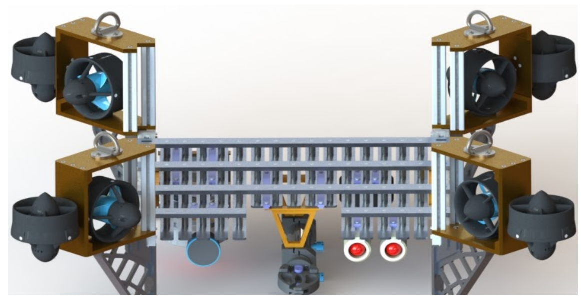


Figure 3. Exposed frame of LANTURN

A modular frame was designed that acts as a hub for mounting components, as shown in Figure 3. The design uses a combination of 6061-t6 aluminum t-slot extrusions and flat bars to avoid complex machining, which contributes to ease of scaling if more mounting surfaces are needed.

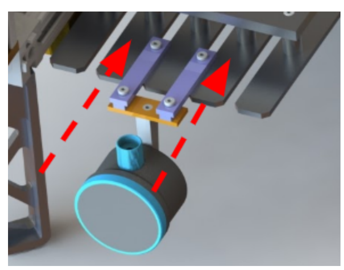


Figure 4. Mounting of sonar sensor

Components, such as the sonar sensor shown in Figure 4, are slid into the t-slot fixture brackets then held in place by tightening one or more set screws.

The claw design for DONPHAN was originally designed to grab a given bar between concave openings at the end of the arms. While these openings do remain, the arms have gotten longer and are placed further apart. This is so that bars can be grabbed either by the end or between the arms. These arms, as well as the parts of the claw assembly outside of fasteners and electronics, are 3D-printed ABS plastic.

The claw assembly itself has three motors, one for each axis. This allows the claw to move in any needed orientation. The electric motors are waterproofed by creating a stuffing box. Square flax thread impregnated with wax is inserted on the inside of the case around the shaft. This keeps water from entering around the shaft and reaching the electrical components.

The dropper design is composed of pieces, excluding the motor, with its core being a rotary disk. The disk is a cylindrical stopper extruding outward and has two slots of where the preloaded markers would be housed. The slots are cylindrical with a diameter of 1.5 inches and a depth of 5.5 inches. The disk rests on a thin 3-D printed cylindrical platform; it has a through hole and a cut path for the stopper to freely move in. A motor sits on top of the disk, held through a shaft slot in the disk's center, and is to be waterproofed through a stuffing box. When desired, the motor would spin the disk; the markers would fall through the stationary platform's opening and be controlled through the stopper slot. To improve accuracy, a funnel is to be bolted to the stuffing box, covering the bottom half of the system.

The concept of the torpedo design revolved around cold gas propulsion systems. There was some debate about which gas would be best, compressed air or carbon dioxide, but the teams final decision was carbon dioxide. Using small 12 gram carbon dioxide tanks, in an adapter for fitting purposes, this propulsion source could then be connected to our on/off switch. For this a direct current solenoid was used with a quarter inch fitting as shown in (Figure 5). The CO_2 tank and adapter can be seen in (Figure 6). At the time of this report there is a single adapter missing for the final concept that would connect the CO_2 tank to the solenoid. Once this is attained final testing of the launching device can begin. More detailed design of the torpedo was then done in order to determine flow characteristics around the chosen design.

Figure 5

Figure 6

The torpedo was designed to slide over the barrel to a depth of 2.3 inches and then attach to an o-ring that would hold it in place until fired. The total length of the torpedo is 4.5 inches which falls within the volume limitations set by the competition. The proposed final design was to machine the torpedo out of brass in order to give it slightly more mass. This enables the torpedo to cut through the water and have an increased trajectory path. While brass is just a proposed material the initial testing material will be plastics used in 3d printing processes. The design can be seen below in (figure 7 & 8).

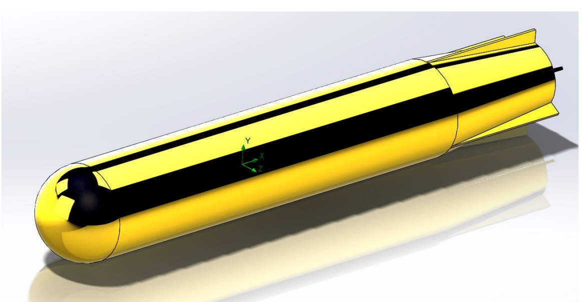


Figure 7

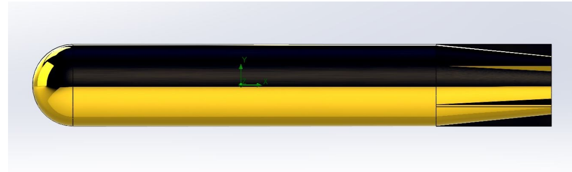


Figure 8

B. ELECTRICAL

The electrical system on LANTURN and DONPHAN consists of a motherboard, a thruster signal routing board, a power distribution board, several microcontrollers, and a sensor suite, all powered by a single 14.8V, 20Ah LiPo battery. Its sensor suite includes:

- Inertial measurement unit (IMU)
- Barometer
- Hydrophones (LANTURN)
- Active sonar module
- Doppler velocity log (DVL) (LANTURN)
- Cameras

As AUV overheating is not an unprecedented issue, our platform was designed using components that would not require an active cooling system. The Jetson TX2 was selected as it is a dedicated system used for deploying computer vision and machine learning applications. Compared to a desktop motherboard and GPU, the Jetson TX2 draws less power and creates less heat with the same performance. This paired with the LiPo battery able to perform up to 65° C will allow us to run the platform for the maximum 20 minutes without causing overheating issues.

In contrast to DONPHAN's previous design, we upgraded our motherboard from a Raspberry Pi 4 to a Jetson TX2 for the same benefits as stated previously in LANTURN. The power system was upgraded to a custom made power distribution board. In addition, an active sonar sensor was added and our LiPo battery rose from 10 Ah to 20 Ah.

C. SOFTWARE

A. Mission Planning

Both platforms software consist of a stabilization controller, several intermediate data acquisition/processing programs, a computer vision system, and a main "mission planning" module for decision making. The software architecture is shown in Figure 9.

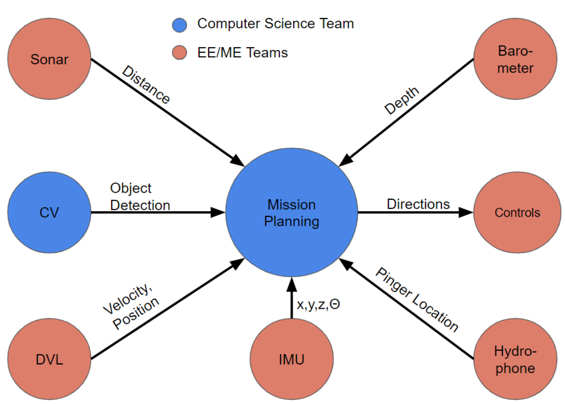


Figure 9: A high level diagram of the software modules.

Each submodule is a stand alone program that has been created to interface with both the sensor it is monitoring and the ROS API to use the Publisher/Subscriber model to send and receive data. This data is sent to the mission planning software running on the motherboard. The mission planning software consists of a machine capable of completing a single defined task. It is based on a loop of searching for an uncompleted task, approaching the task, executing the task, and disengaging/tracking completed tasks. Each sub-state is responsible for obtaining relevant data from the sensor modules, as well as controlling the submarine. Each sub-state is unique to the task, allowing the programming and testing of a specific task without the need to have the entire state machine running.

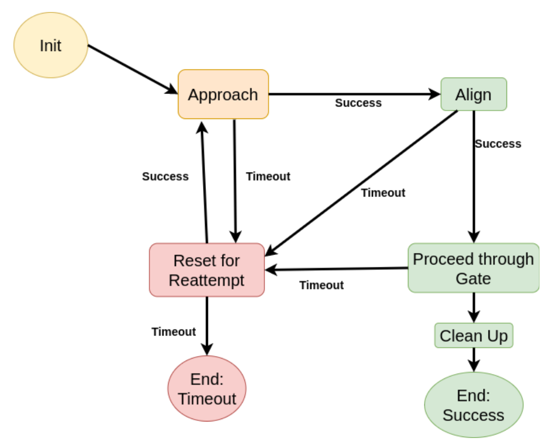


Figure 10: Example Gate Sub-state Machine

It also allows for setting a time limit on tasks, allowing the submarine to move on if the task takes too long to complete. The modularity of this system will allow for greater reuse of code, simplifies testing of specific functions and substates, as well as faster modifications without disturbing the function of other task states.

B. Computer Vision

The vehicles are able to detect, classify, and localize objects underwater. To accomplish detection, classification and localization of objects underwater the team used Deep Learning in the form of Convolutional

Neural Networks (ConvNet). This is a type of deep neural network inspired by the human brain visual cortex. The algorithm implemented is YOLOv4 (You Only Look Once) and can detect objects and their locations/sizes simultaneously, and while training and testing YOLO sees the entire image. It does this by considering object detection as a regression problem to assign class probabilities to spatially separated bounding boxes. Yolo was selected as it is one of the Convolutional Neural Network (CNN) approaches with the best speeds in object detection allowing for faster response times to stimuli.

Images were taken from the 2019 Robosub competition to train and test computer vision software. The dataset was labeled and outlined with proper bound boxes. These were used to train the CNN with the dataset of images to be able to produce custom weights files. These weight files are the trained system, able to be implemented on the platforms by uploading them to the motherboards.

C. Controls

The controls module computes the necessary stabilization motor commands, and then sends both the computed stabilization commands and the movement commands from mission planning to the motors to both stabilize and move the platform.

A model of LANTURN was created on Simulink simulation software, a complementary software to the MATLAB coding language. The purpose of this model is to create and test control system algorithms and tune PID controllers. This model operates on a 6 DOF platform, contains the physical properties of LANTURN and has the dimensions relating the location of the eight thrusters to the center of mass. The moments of inertia, mass, and buoyancy properties were taken from the Mass Property tool in the SolidWorks model.

Two different controls software were created due to the orientation and number of thrusters on each of the platforms. LANTURN has an extra degree of movement that can be accessed, and movement on the horizontal plane can be achieved using all four horizontal thrusters. Due to the similar locations of the vertical thrusters, that part of the control code is reused, with appropriate changes to the PID constants.

The traveling system works similar to a car which can go forward or backwards and yaw to point the nose in the desired direction. Elevation gain is achieved solely through use of the vertical thrusters, without rotation. This control system is in its infancy and is not currently functional.

One of the main hurdles of this model is tuning PID controllers. This task is notoriously time consuming when tuning on a physical prototype. Simulink has a tool which can easily tune PID controllers to different behavior patterns and cuts down on physical testing significantly. A proof of concept for the ability to tune a PID in Simulink and use it on a physical prototype has been done on a custom drone. A drone was built, a model was made in Simulink using a similar algorithm as for the AUV model, and the PID controllers were tuned to balance the drone. The PID constants were then implemented in the drone and the drone was able to balance itself automatically. This shows that the work done in Simulink will translate to significant time saved on testing the AUV prototype.

EXPERIMENTAL RESULTS

Hull

The hull was analyzed using SolidWorks' static-stress analysis. The deepest the RoboSub would have to go to is 16 feet or 5 meters which corresponds to a pressure of 49,000 pascals. Under these conditions a factor of safety of 1.1 was found, which definitely needed improvement. The highest stress was found on the corners on the top sheet, so all adjustments focused on that area.

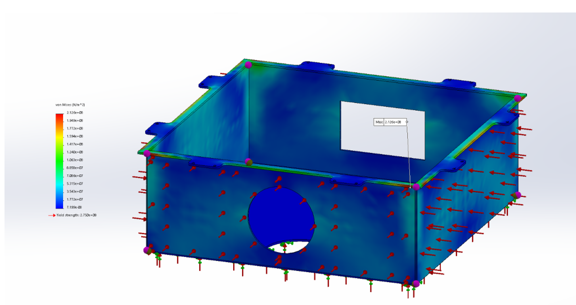


Figure 11: Stress analysis on hull

Three adjustments were made on the hull to increase factor of safety; increasing the thickness of the top sheet from ⅛ in to 3/16 in, extending the top sheet outwards by 0.2 in, and adding 1.5 in chamfers to the corner of the top sheet. All three adjustments increased the factor of safety to 3.1 which is very satisfactory.

In order to evaluate the efficacy of the welded AL 6061 design of the hull in withstanding the stress produced as a result of latching and unlatching the lid latches, static and fatigue stress analysis was conducted. SolidWorks' built-in weld size calculator, which leverages static stress analysis data, was used to calculate a first-order estimate of required weld bead size.

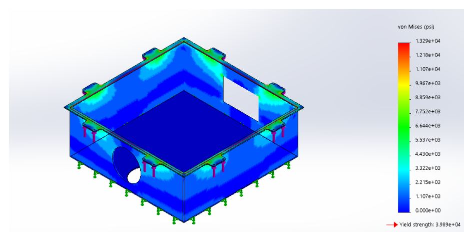


Figure 12: Determination of required weld-bead size via stress analysis

These results were then further verified through fatigue stress analysis in ANSYS. For this study, symmetry was leveraged and a ⅛ model of the loading condition was simulated, which allowed for a more refined mesh and higher fidelity results.

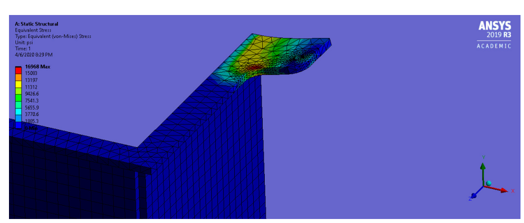


Figure 13

To determine the accuracy to which the developed hydrophones system could determine the heading angle of a high frequency sound, the hydrophones system was tested in a body of water by placing a pinger a few yards away from the hydrophone array and recording the calculated angles while the approximate “theoretical” angle was known. The array was tested at “theoretical” angles incremented by 45°. The system was able to consistently produce the correct heading angle of the pinger.

LANTURN’s computer vision system was also trained on several of the competition images, and its accuracy was found to be sufficient for detecting these images underwater. A preliminary version of LANTURN’s ROS architecture showed its functionality in cooperation with the other systems on the submarine.

Heat

The beginning of this analysis started with rough hand calculations to quickly establish the general state of Lanturn’s internal thermals. Worst case and realistic case scenarios were considered. The following were the relevant parameters and assumptions used: Lanturn’s hull size and material type, the water temperature that Lanturn will operate in, the most heat sensitive internal component(s), and the total max heat generation from the internal components. The worst case scenario considers the following: 20°C water temperature, 85 to 100W of internal heat generation, and the lowest textbook value for convection heat transfer coefficient (2 W/m2K) [4].

A more realistic scenario considers the same conditions but with 50W of internal heat generation – Lanturn is unlikely to be operating all its internal components at maximum power all at the same time. The most heat sensitive internal component of Lanturn is its battery, which is rated to operate at temperatures up to a maximum of 65°C.

Under both estimated worst case and realistic scenarios, this initial analysis determined that overheating would be a distinct possibility for Lanturn’s battery. With this in mind, a more thorough investigation by SolidWorks was performed. The full SolidWorks model of LANTURN with all its components defined proved too cumbersome to work with in both the basic Simulation feature of SolidWorks and the add-in feature of Flow Simulation. Thus, a simplified model of Lanturn was created for a temperature Flow Simulation. This model consists of two trays and six blocks scattered around in Lanturn’s hull, shown in Figure 31. This figure also shows example heat generation values for each component.

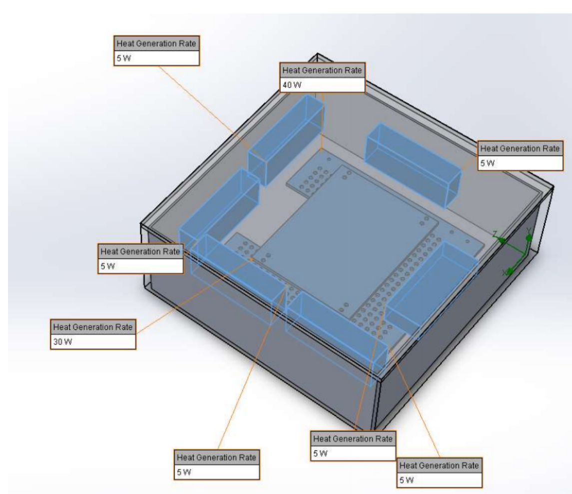


Figure 14

One tray was set at 30W and the other at 40W. Each block was set at 5W. This simulates the assumed worst-case scenario of a total heat generation of 100W. The hull walls, top, and bottom were set as 20°C boundary conditions to simulate a submerged water environment. The Flow Simulation results at a pseudo steady state are as follows: The two trays were at over 100°C and the six blocks ranged from about 65 to 115°C. Crucially, the average air temperature was about 50°C. If necessary, a heat exchanger can be used to cool a component with this air. The more realistic scenario of a total of 50W of heat generation (where the two trays were changed to 10W of heat generation), returned temperatures for the eight components ranging from 56 to 95°C and an average air temperature of 36°C. With these two scenarios in mind, it is safe to say that overheating is not a current concern for Lanturn's internals. However, the steady-state nature of this analysis is a limitation.

Torpedo

After the final design geometry had been selected flow simulations were conducted to further analyze the structures practicality. Below in (figure 15) the vorticity profile of the torpedo when moving at 5 m/s at a depth of 3 meters is shown. Vorticity is a representation of the rotational characteristics of the fluid flow. In (figure 15) it is clear that the flow immediately turns turbulent after passing by the end of the tail. This creates low pressure zones that could slow the torpedo down. Yet, with the brass design and added mass the torpedo could carry additional momentum that would prevent these immediate effects.

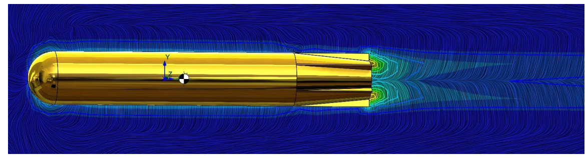


Figure 15

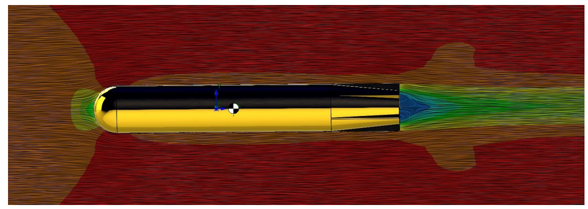
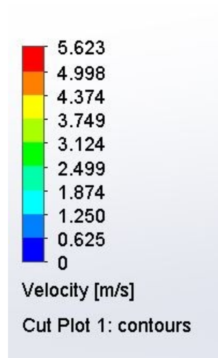


Figure 16



Above in (figure 16) the torpedo is undergoing a velocity profile test. The free flowing stream is around the torpedo indicated by the red showing the movement of the water unaffected by the torpedoes movement. However, the fluid in front and behind the torpedo has about half the velocity of the surrounding flow. At the tail in the blue region the velocity falls to nearly zero as the turbulence distorts the streamline motion of the water particles.

The final test that was done was for the pressure variation of the water around the torpedo. This is shown below in (figure 17). The yellow regions show higher pressure zones around the nose of the torpedo while the blue zone around the tail represents a low pressure zone.

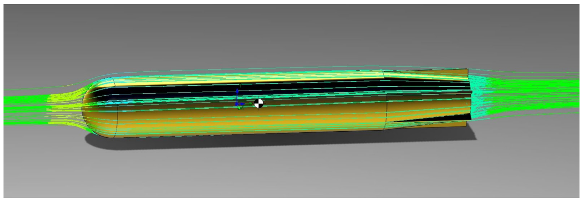


Figure 17

Computer Vision

Our network is trained using Darknet, an open source neural network framework, and given a dataset of images which have been labeled to distinguish the objects we want to detect. The algorithm was trained on over 4 thousand images and was trained to detect 12 unique objects. The training was done over a 50 hours period and had gone through 24 thousand iterations and had processed over a million images. After the training of our Convolutional Neural Network we then tested it on a video of the competition. As seen below, the results were positive with a majority of the objects being detected with a confidence of over 80%. Object tracking was consistent, with minimal time of lost object recognition while on screen.

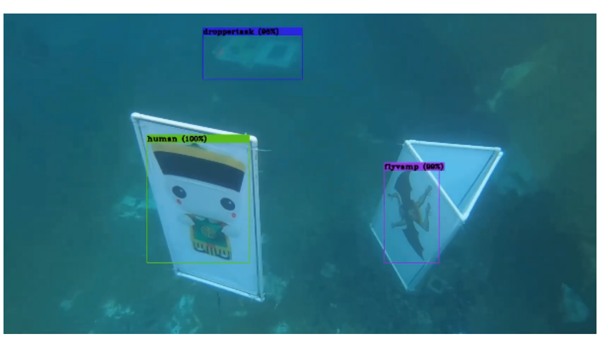


Figure 18

This is a massive hurdle our team has struggled with in previous years, and our efforts here have allowed us to streamline the process for training and testing computer vision models for future competitions.

ACKNOWLEDGEMENTS

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