PopEye: The first step towards auto-anchoring for commercial vessels

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***Abstract*— Technological advances in artificial intelligence, robotics, and autonomy are allowing ship owners to reduce crew duties and take advantage of highly accurate and technical sensors for standard ship . Currently, 80,000+ commercial vessels mandate human anchor-watch for every hour that a ship is at anchor. Data collected from primary and secondary sources suggests that the current methodology is highly prone to human error, is extremely dangerous for both ship operators and the environment, and costs shipowners tens of thousands of dollars in maintenance, repairs, replacements, and wasted fuel. PopEye Labs has created the world's first 24/7 anchor-monitoring system for commercial vessels- automating anchor-watch using state-of-the-art computer vision and an adaptable artificial intelligence system. This paper will develop a clear understanding of the capabilities and limitations of this technology and how it can be used to improve maritime safety, cut down operating costs, and pave the path towards full vessel autonomy.**

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I. INTRODUCTION

The maritime industry refers to all activities related to sea transportation of goods, including shipping, shipbuilding, port operations, and marine equipment manufacturing. The industry is a major contributor to global trade, with around 90% of all goods transported by sea. The industry also employs millions of people worldwide, including seafarers, port workers, shipbuilders, and maritime lawyers, among others.

A. Automation

The commercial shipping industry is currently undergoing a significant shift towards automation and autonomy. According to a report by the International Transport Forum, "The use of autonomous ships is expected to increase efficiency, reduce costs, and improve safety." This shift is driven by a variety of factors, including increased competition, rising fuel costs, and stricter environmental regulations. As the industry shifts toward this $5.8 billion autonomous ships market, seaborne trade is projected to double.

One of the key drivers of automation and autonomy in the commercial shipping industry is the need for increased efficiency. Shipping companies are under constant pressure to reduce costs and improve their bottom line, and automation can help achieve this by reducing the need for human labor and increasing the speed and accuracy of operations. Similarly, automated systems can be used to load and unload cargo, as well as automating mundane tasks such as monitoring on the ship reducing the need for human labor. Autonomous vessels will weigh 5% less, consume 12-15%

less fuel, and offer 22% in total savings per ton carried.[6]

Another important driver of automation and autonomy in the commercial shipping industry is the need to reduce emissions and comply with stricter environmental regulations. Automated systems and machines can help achieve this by reducing fuel consumption and lowering emissions. As stated by the International Maritime Organization, "Automated navigation systems can be used to optimize routes and reduce fuel consumption." Additionally, "automated cargo handling systems can be used to reduce emissions from cargo handling operations." Maritime transport represents 2.9% of total greenhouse emissions worldwide.[7]

The future of the commercial shipping industry is likely to be shaped by automation and autonomy. Within the next 10 years, 5% of all seafaring vessels will be fully autonomous.[6] This shift will bring significant benefits to the industry, such as increased efficiency, reduced emissions, and improved competitiveness. However, it will also bring challenges, such as the need to train and retrain workers, and the need to adapt to new technologies.

B. Malpractice

When it comes to technological advancement, the maritime industry has been lagging behind. The RMS Titanic sank in 1912, yet remarkably it wasn't until last year (December 2022) that the onboard technology developed allowing individual ships to detect iceberg threat. The same is true of many of the operations undergone on commercial vessels on a daily basis, including anchor-watch.

With seaborne trade expected to double by 2030, and without adapted operational systems in place, there will be an exponential increase in the number of crew mate injuries, lost anchors, tarnished seafloor, and wasted fuel experienced annually.

C. Source of Innovation

With the world's first around-the-clock, autonomous anchor-monitoring system, PopEye offers a solution that addresses current flaws in ship operation **and** one that's necessary for the development of all future autonomous vessels. At the intersection of mechanical design, electronics, and computer vision, PopEye both solves the problem of anchor loss, malfunction, and danger, and takes the necessary first step toward fully autonomous, more sustainable anchoring for large commercial vessels.

Fig. 1. PopEye Prototype 4 designed in SolidWorks

II. PROBLEM STATEMENT

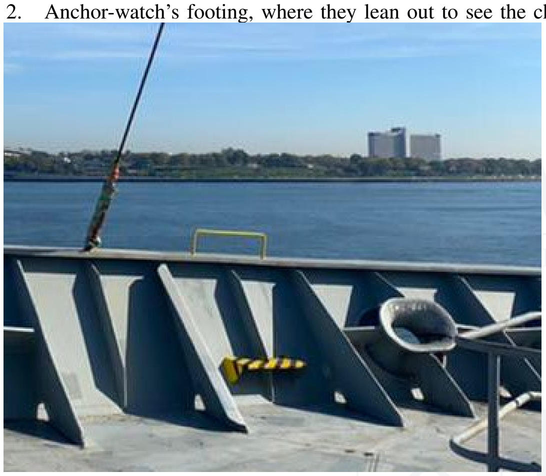
To best understand the relevance and impact of PopEye's technology, we offer a situation-complication-resolution framework.

A. Situation

Large commercial vessels anchor outside ports at anchorages, waiting to enter port for days or weeks at a time.

Anchor-watch is an integral part of the deck officer's duties. Inspections are performed to guarantee anchor health, ship positioning, and incident avoidance. Every 15-60 minutes anchored, a person i.e. "anchor-watch" is required to walk to the front of the ship to observe the chain. The watchman, commonly nicknamed the 'popeye', relays their interpretation of the direction and slack in the chain back to the captain. Every 4 hours, that anchor-watchman must switch posts, and a new watchman takes their position.

Fig. 2. Anchor-watch's footing, where they lean out to see the chain



B. Complication

Visual reporting is both highly subjective and unreliable. During the time between regular anchor checks, multiple things can, and do, go wrong. Deck officers often get hurt in extreme weather conditions. 1.9k injuries are sustained on commercial vessels annually, of which a majority are attributed to working the anchor. Weather-induced horsing motion can stretch the chain causing brakes or swivels to break and the anchor to be lost– a $2M expense for the company. 700 commercial vessel anchors are lost and replaced annually. Improperly set anchors drag. 8k square miles of seafloor is tarnished annually. Dragging in turn can cause ship collisions inside tight anchorages, damages if a ship is "beached", and extra fuel spent on re-anchoring maneuvers. 1.3k gallons of diesel fuel are wasted per ship per day spent in an anchorage on re-anchoring alone. 200 vessels are beached every year. 600 vessels collide every year.

C. Resolution

At the bow of the vessel, we propose attaching an Infrared camera inside an anti-corrosive box to the ship. The solution 'uninvasively' latches to the bow of the vessel (directly above the protruding chain) and is able to see the chain and collect data continuously under all weather conditions. We utilize state-of-the-art computer vision to predict the chain movement, direction, and slack. We detect anomalies and store video for potential insurance claims. On the bridge, the officer on deck can continuously monitor the tension and direction of the chain, as well as the location of the anchor in 3-dimensional space. Alerts are automatically triggered directly on the bridge when action is needed from the officer, for example, in the case of a dragging anchor. For international vessels, we also offer a package containing two additional modes: 'man-overboard' and 'pirate'. Using the same system cameras, and adapted vision, our solution is able to timestamp and position human presence on the outside of the vessel– an issues that plagues seafaring commercial vessels.

III. TECHNOLOGY

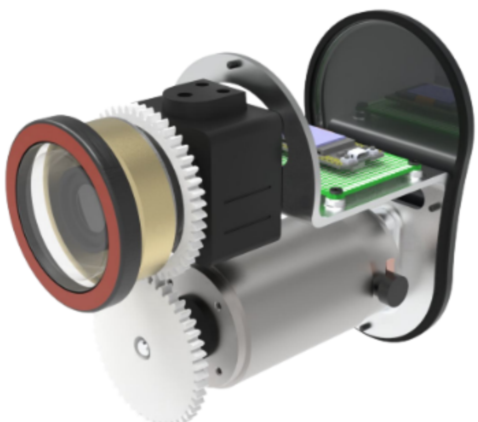
A. Enclosure

PopEye machinery must be able to operate in one of Earth's most difficult environments, a combination of: freezing cold, saltwater spray, ship vibrations, direct sunlight, and more. Capt. Angelos Giannakopoulos' initial response that "no electronics survive at the bow of a ship", largely shaped our mechanical engineering design and fault tolerance testing. The casing must be waterproof, able to withstand corrosive influences, and hydrodynamic. We've employed industry standard, galvanic corrosion-resistant materials to ensure these requirements are met.

B. Rotating Lens

In order for our camera's to be able to "see" the anchor's chain, it's pivotal that our protective lens remains droplet free. To accomplish this, our enclosure includes a DC motor operating at roughly 700RPM that rotates our casing's acrylic lens. This speed of revolution has been tested to consistently 'flick' off all debilitating water droplets at a necessary rate, and is powered by the vessel's internal power source.

Fig. 3. Rotating lens exploded view



This type of system has never been curated at this scale, prompting us to take on two intellectual property advisors. After completing prior art scrubs across US, European, and Chinese patent databases, we've found that PopEye's mechanical technology is patentable.

C. Dehumidifying and Interior Heating

In this type of environment, with highly variable external temperatures, our acrylic lens can be prone to fogging. To counteract this our enclosure will feature a temperature probe coupled with modern conductive tape that connects to copper-wiring. This allows the enclosure to maintain a working internal temperature just off of the the vessel's power, regardless of external temperature. We've also fitted silica desiccant packets into the system with 1.5 year half-lives to tackle excess moisture.

D. Electronic Components

Safely inside our PopEye waterproof casing lies a Jetson Nano which runs the computer vision prediction script together with a LoRa microcontroller for communicating with the bridge and a GPS module which is able to tell us our geographical coordinates accurately. Our power supply is hybrid since we have an in-house battery component able to run independently for up to 7 days straight. We can also connect directly to the power supply of the ship in a waterproof and secure manner. All electronics within the system have been tested and configured to be intrinsically safe (IR).

E. Computer Vision

Utilizing computer vision, PopEye offers the world's best chain-detection algorithm and analytical model. Computer vision is a field of artificial intelligence that enables computers to interpret and understand visual information from the world, such as images and videos. One of the most popular and 'state-of-the-art' computer vision algorithms available is YOLOV5, standing for "You Only Look Once Version 5". This algorithm is designed to detect and classify objects in images and videos. It works by analyzing the input image or video, breaking it down into smaller regions, and then using a deep neural network to identify the objects within those regions.

In PopEye's case, we took a pre-trained YOLOV5 algorithm and additionally trained it on 600 different images of chains found across the internet. Our results were largely encouraging with MAPE 46.1%, and are more than accurate enough for our use case as seen on Figure 4.

Identifying each individual chain link is critical for completing the calculations of (a) how much chain has been paid out during the setting of the anchor and (b) estimating the amount of chain above-water.

Fig. 4. Raw image from camera

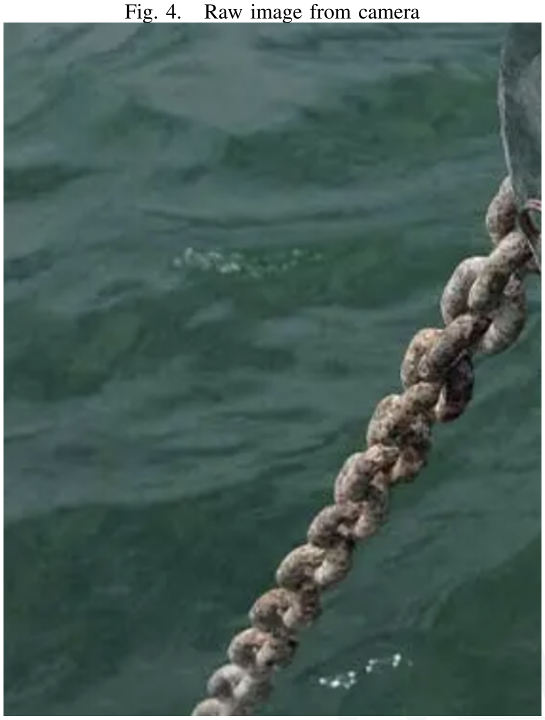


Fig. 5. Chain Link Object Detection, using YOLO

F. Camera system

At sea, PopEye will frequently encounter the following adverse circumstances (size of "droplets"):

- Haze like particles from salt crystals, dust or combustion (<0.5μm)
- Continental fog (3μm)
- Marine i.e. coastal fog (17μm)
- Ice fog (400μm)
- Drizzle rain (500μm)
- Normal rain (2000μm)
- Heavy rain (4000μm)
- Snow (5000μm)

In order to maximize our chances of being able to see through these particles, as well as direct sunlight and moonless darkness, and all combinations thereof, we are using a Near InfraRed (NIR) at 800nm camera in combination with a LongWave InfraRed (LWIR) at 14000nm camera. In addition, for circumstances where not enough illumination is provided by the environment, PopEye can activate InfraRed light pointed at the chain, allowing the system to see in complete darkness. This light is invisible to the human eye so as not to alert nearby ships at the anchorage.

G. Mathematical Estimations

The two most important tasks we need to get values for are what the anchor-watchman reports to the bridge: (a) the angle on a horizontal plane (12 o'clock being forward from the ship) and (b) the tightness of the chain.

Task (a) is more simple, as we trace the line that connects detected chain links with reference to the ship. However, task (b) is a bit more complex for a machine to measure. Here's our key assumption, which we have validated in discussion with hundreds of captains, anchor-watch deckhands, and maritime professionals:

> *Assumption #1: The tension of the chain is directly relative to how far from the ship the chain enters the water.*

Under Assumption #1, if we know the length of the ship's chain link *a priori*, and we can count the number of links, then we automatically know the length (meters) of chain above water. In case of wave activity, we apply a simple filter and get an accurate approximation. Our next assumption helps us go a step further:

> *Assumption #2: The visible portion of the chain that is above water is always a straight line.*

We also know the load of the ship *a priori*, which in turn allows us to estimate the shape of the whole catenary of the chain including the percentage of the chain that touches the bottom of the sea, since we know water depth at any given point[1]. Then, knowing how much chain has been paid out already helps us pinpoint the direction of the actual anchor. As the ship swivels around it's anchor, we can accurately pinpoint the specific location (in longitude and latitude) of the anchor. PopEye is able to track these changes over time.

Knowing the location of the anchor, using our PopEye's GPS location, and knowing the catenary shape, PopEye easily recognizes a dragging anchor– in which case the system immediately alerts the captain. With this information the captain knows when the anchor is actually set immediately from the point of release. The main cause of anchor-dragging is an originally improper set of the anchor. This proactive dragging prevention is what allows PopEye to save shipowners 650+ gallons of fuel per day spent in an anchorage (equating to 3.4M tons of CO2 per year globally).

Of equal significance is knowing when the ship is going to drag **ahead of time**. This information allows a captain to put engines on standby and be ready to heave anchor without causing harm to the rest of the anchorage. The following two assumptions help us with just that.

> *Assumption #3: A given seabed has a static friction coefficient.*

> *Assumption #4: 80%+ of the holding power comes from the chain static friction, not the anchor.*

[1]Seafloor Depth Engine, Google Earth

When a ship starts to drag anchor, there's a recognizable tipping point: the chain friction and the anchor don't provide enough holding power. This moment is key because, from it, we can compute the missing parameter in our catenary estimations: our static friction coefficient (μ_{static}), which we argue is unique for the specific seabed at the specific location of the anchorage. After collecting enough data on enough dragged anchors inside an anchorage, we can actually predict at what tension of the chain the ship will start to drag.

Taking this a step further, knowing the weather conditions at the ship's location and the recent history of the ship chain's tension, we can actually predict *when* the ship will start dragging, offering a timely and proactive alert on the bridge.

H. Website on the Bridge

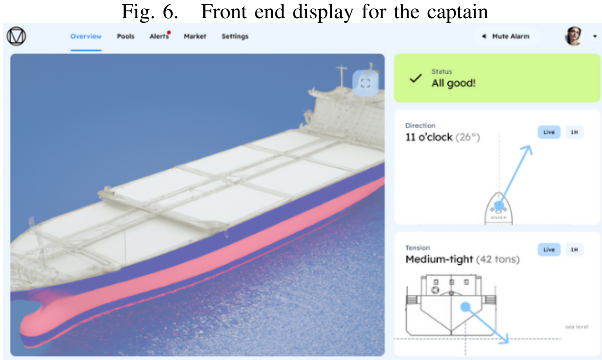
Via a local network LoRa, without needing access to the internet, our PopEye from the bow of the ship easily communicates with an iPad or any other device that is at the Bridge. From a simple website, the officer can (a) monitor 24/7 the chain and anchor Key Performance Indicators (KPIs), (b) be alerted of imminent threat of dragging anchor and (c) change settings of the whole system.

IV. BUSINESS CASE

A. Value Proposition

Ship Owner or Operator. PopEye is projected to save shipowners roughly $19,250 on diesel fuel annually as a result of less re-anchorings. Furthermore, the ship operator can complete the same duties with fewer crew members, since the particular anchor-watch duty is replaced by PopEye's technology. In addition, the ship owner mitigates risk of losing anchor, risk of side-ship paint being scraped off, and risk of ship collision, all of which translate to cost-savings. The dangerous task of walking at 3am on the frozen deck at the bow of the 200-meter ship is avoided, resulting in improved safety conditions for the crew. When human or equipment accidents do happen, we offer a system of record to the insurance company that can help the ship manager avoid incurring costs.

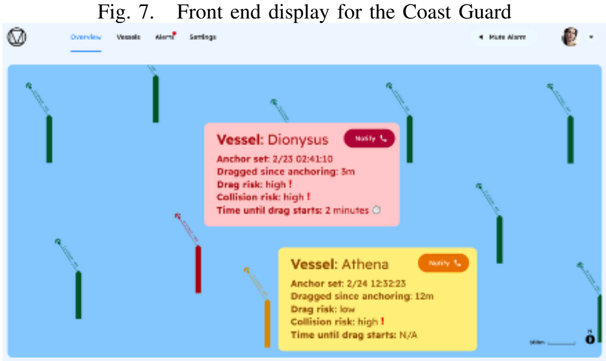
Fig. 6. Front end display for the captain



Port Authorities and Coast Guard. What the port authorities and the Coast Guard care most about is safety. Currently, these entities rely on visual inspections and the Automatic Identification System (AIS), the latter of which solely reveals the position of a ship (not anchor) without any predictive or proactive measures. In the case of typical anchor drag, combined with delayed crew procedures, one ship can cause environmental disasters due to oil pipes being hit, or millions of dollars worth of port damages due to ship collisions.

When every ship at an anchorage is using a PopEye device, the network of them provides port authorities with a 'Bird's Eye View' of the anchorage which serves as a layer of pro-activeness that the currently lack. In short, we offer continuous monitoring capabilities, accident-prevention, environmental protection, and the ability for stakeholders to be proactive rather than reactive.

Fig. 7. Front end display for the Coast Guard



B. Total Addressable Market (TAM)

PopEye is priced at USD$15,000 per vessel per year, including installation and maintenance of the system. In the future, where scale is sufficient, we will commercialize aggregate analytics on the port and anchorage-level toward insurance companies as well as port authorities and the Coast Guard. Our TAM is USD$1.2B, given the 80,000+ commercial vessels worldwide and the USD$15,000 price tag per vessel.

C. Competitive Landscape

There is currently only one competitor attempting to do adjacent work. Shipin.ai uses footage from *existing* CCTV to make manual inspection labor obsolete. However, no large vessel today has a camera installed at the bow of a ship looking outside of the ship. Unless shipin.ai moves into hardware and design of camera systems, we remain the only player in this space.

Companies like Yara International have helped design the first autonomous voyage across the Atlantic [2] and now might move into automating the anchoring procedure. However, given our extensive research, performing the actual voyage in an empty ocean might be less complex than actually navigating a tight anchorage and performing multiple anchoring procedures and monitoring.

The key competitor, though, is the current state of affairs, where a human i.e. anchor-watch walks up to the bow of a ship every one hour to look at and report on the chain. Making an stand against the inertia of the status quo requires significant sales talent and of course the establishment of a customer pain.

D. Unit Economics

With a Cost of Goods Sold (COGS) of $2.5k, and annual maintenance projection of $1k, PopEye shows an 8:1 Cus-

[2] https://electrek.co/2021/08/25/worlds-first-autonomous-7mwh-electric-cargo-ship-to-make-voyage-with-zero-crew-onboard/

tomer Lifetime Value (CLV) to Customer Acquisition Cost (CAC) ratio.

V. IMPACT

When the PopEye team originally came together to set a foundation for fulfilling this need, one of our key non-negotiables in choosing a path forward was “impact”. PopEye’s ESG relevance and significance is undeniable.

A. Global Reach

This system directly influences the global commercial vessel fleet. With over 80,000 commercial shipping vessels (ship length greater than 500 feet) actively in service today, the repercussions of PopEye will be worldwide. Furthermore, PopEye has the capacity to expand into the recreational-use space. With this market expansion, PopEye’s customer potential figure exponentially grows into the millions.

B. Environmental

One of PopEye’s main selling points is its positive impact on the environment. Anchor dragging accounts for over 6000 square kilometers of ocean floor damage annually. Moreover, one of every 100 commercial vessels loses its anchor annually. Even in its most elemental state, PopEye will directly counteract these two catastrophic situations.

C. Societal

Industry trends show that commercial shipping is moving toward autonomy. From an efficiency standpoint, autonomous vessels offer both the most practical and safest solution to the commercial shipping industry. Autonomous anchoring is a key step in being able to achieve this autonomy, and a milestone that PopEye is directly contributing toward. Equally as significant, over 1900 non-fatal injuries occur on commercial vessels annually, of which a significant portion can be allocated to winch system operation, anchoring, and general deck malpractice. By moving away from subjectivity in anchor monitoring, and no longer requiring human operation, there is far less room for error.

VI. TEAM

Our interdisciplinary team is comprised of top talent from both the Engineering School and The Wharton School at University of Pennsylvania. Together, we study in the relevant fields of Mechanical Engineering, Computer Science and Electrical Engineering with industry experience at Tesla, McKinsey & Co, Zoox, The Boring Company, Wharton Research Lab, Atomic VC, Toyota Racing, as well as various startups.

Our team’s advisors and partners span world-class computer vision scientists like Professor Kostas Daniilidis, to industry-veterans like Professor Nicholas McGill-Gardner, to maritime experts like USMMA Capt. James Zatwarnicki, to high-ranking Coast Guard officials like CG-5P Katie Burkhart.

VII. FUTURE WORK

PopEye Labs considers the monitoring of the anchor chain just the first step towards autonomous anchoring without human intervention. The next step to our system’s development is to enable the setting, monitoring, and heaving of the anchor without human assistance or oversight. We will be able to employ the same predictive vision technology, coupled with mechanical innovation, to interact with the winch in raising and lowering the anchor.

VIII. ACKNOWLEDGMENTS

The team would like to thank Professors Nicholas McGill-Gardner, Siddharth Deliwala, and Jan Van der Spiegel for their support and guidance throughout the development of this project. We further thank the Department of Electrical and Systems Engineering at the University of Pennsylvania for funding our work and providing us with a testing environment. Finally, we would like to highlight ex-’popeyes’ US-

MMA Capt. James Zatwarnicki and CG-5P Katie Burkhart for their dedication to helping us deliver a relevant and impactful system to the maritime industry.

IX. ADDITIONAL REFERENCES

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