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Design of an Automated Floating Station-Keeping Power Line (AFSPL) for Ship-to-Shore Humanitarian Aid Delivery

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Abstract: Transfer of humanitarian aid from cargo ships face severe constraints when port infrastructure is inaccessible. Traditional intermediate transport methods include ferry vessels, helicopters, and trucks on floating causeways, none of which can meet operational targets for time, cost, and throughput. Advances in technology enable the use of heavy-lift electric drones that transfer aid faster and cheaper. An enabling technology for electric heavy-lift drones is a Catenary Aerial System (CAS). The Automated Floating Station-Keeping Powerline (AFSPL) system utilizes a network of autonomous floating utility poles equipped with onboard station-keeping propellers that maintain fixed positions in dynamic ocean conditions. A stochastic simulation model and 3-DOF PID controller validated in MATLAB were used to evaluate system feasibility. The electric heavy-lift drone with the AFSPL delivers 1,000 pallets in an average of 6.68 days at $233.80/pallet, satisfying all performance targets. These results confirm the AFSPL is a viable solution for ship-to-shore aid delivery.

Keywords: Humanitarian Aid, PID Controller, Simulation Model, Cargo Transport

1. Background

1.1 Introduction and Context Analysis

Humanitarian crises in developing countries often occur in fragile environments where natural disasters or armed conflicts destroy critical infrastructure, isolating populations from essential resources. According to U.N. OCHA, Over the last 10 years, an average of 380 natural disasters have required humanitarian aid delivery annually (OCHA, 2024). During these crises, international humanitarian organizations coordinate large-scale relief operations and transport aid via cargo ships anchored several miles off the shore of affected regions. Transferring aid from ship-to-shore remains a major logistical bottleneck, forcing humanitarian organizations to rely on inefficient methods such as helicopters, trucks on floating causeways, or small boats, often requiring support from governments, militaries, and private contractors. Given a 90-day humanitarian operation aiming to feed ~30,000 people, current intermediate transport methods fail to meet either cost and/or throughput requirements. While advances in technologies like heavy-lift electric drones have been proposed, current drones suffer from heavy batteries, limiting payload capacity. As a result, current ship-to-shore aid transfer remains one of the biggest pain-points, preventing humanitarian organizations from delivering aid quickly and efficiently to people in need. This paper presents the design and feasibility analysis of the Automated Floating Station-Keeping Power Line (AFSPL). The AFSPL is a network of autonomous floating utility poles that establish a catenary power line between a cargo ship and shore to enable continuous heavy-lift electric drone operations. This paper follows the outline provided by the systems engineering vee-model starting with a context analysis and finishing with a business plan.

1.2 Stakeholder Analysis

Stakeholders in the ship-to-shore logistics system represent a broad network of actors that are interdependent and have specific roles, goals, and issues (Table 1). To determine what stakeholders are part of the system, case studies and interviews with subject matter experts were performed. 13 stakeholder interviews were conducted with representatives from organizations such as the U.N., World Bank, International Red Cross, and U.S. Army.

Table 1: Stakeholder Analysis for Moving Humanitarian Aid

Stakeholder	Roles	Tensions

Local Citizens	Receive food, water, and medicine in a timely manner.	Delays in aid delivery cause malnutrition, dehydration, and the spread of preventable diseases.
Politicians	Approve or block operations; maintain public support.	Delivering aid while maintaining political stability.
Local Government	Maintain stability between politics and citizens; coordinate with humanitarian organizations.	Faces political fallout if corruption occurs.
International Entities	Provides funding, resources, and international coordination.	Restricted by political alliances.
Int. Humanitarian Organizations	Lead and manage humanitarian aid efforts.	Dependance on costly, slow, unavailable ship to shore methods.
Logistic Managers	Coordinate ship-to-shore transfer operations.	Limited by weather/sea state and budget.
Engineers & Contractors	Build and maintain infrastructure; move cargo	Limited by weather and time
Local Humanitarian Organizations	Act as a vessel between international organizations and local connections.	Locals may be distressed and/or cause issues with international organizations.
Local gangs and militias	Maintain control of captured supply chains.	May cause problems with humanitarian organizations by demanding bribes.

2. Methodology

2.1. AS-IS Process and Simulation

Three independent ship-to-shore transportation processes are defined for the current as-is process being the trucks on floating causeways, helicopters, and boats. Each process involves 12 actors and 20 steps. The Floating causeway setup alone takes over 60 days and costs over $200M (Gardner, 2018; U.S. Naval Institute, 2023). Boats face speed constraints and fail to meet throughput targets under typical maritime conditions. Helicopters are frequently used for rapid response but are difficult to scale and are too costly for long term sustainable missions (Boeing Defense, n.d.; U.S. Army, n.d.).

A stochastic simulation model compares the different methods of transportation available. The results were then used to determine the performance gaps and performance targets of the system. The simulation is based on the following assumptions: There are no hardware breakdowns, there are no breaks for workers or perfect rotations, there is only one cargo ship (one resource node), and vehicles perfectly predict when another is done loading. The vehicles load on the ship and unload on the shore. Some vehicles will not be able to move cargo on certain days; this will be determined by the sea state and weather conditions. Simulation parameters in Table 2 below were derived from were derived from published U.S. military vehicle specifications and operational documentation, including Boeing CH-47 specifications, U.S. Army Palletized Load System specifications, and U.S. Marine Corps program handbooks (Strategic Logistics Division, 2014; U.S. Marine Corps, 2016; PEO CS&CSS, n.d.; Boeing Defense, n.d.; U.S. Army, n.d.).

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Table 2. Simulation Parameters

Parameter	Helicopter	Boat	Truck
Pallet Capacity	10	20	10
Speed (mph)	triangular (0.8*20, 20, 1.2*20)	triangular (0.8*9, 9, 1.2*9)	triangular (0.8*9, 9, 1.2*9)
Sea State Limit	4	3	3
Weather Limit	5	5	4
Sequential Hours of Operation	10	12	10
Setup Cost ($)	0	0	2*10e+8
Cost per Day ($)	40000	10000	2500
Setup Time (days)	2	1	60
Loading Time (minutes)	triangular (0.8*5, 5, 1.2*5)	triangular (0.8*45, 45, 1.2*45)	triangular (0.8*45, 45, 1.2*45)
Time until next fuel (hours)	3.5	18	15
Fueling Time (minutes)	triangular (0.8*45, 45, 1.2*45)	triangular (0.8*30, 30, 1.2*30)	triangular (0.8*30, 30, 1.2*30)

The results from the simulation model are shown below:

Table 3. AS-IS Simulation Results (3 Vehicle, 1,000 Pallets)

Boat	Time (Days)	Op. Availability (%)	Total Cost ($)	Cost per Pallet ($)
Average	10.87	43.69	296,000	296.23
Std. Dev.	3.71	10.5	111,356	111.851
Helicopter	**Time (Days)**	**Op. Availability (%)**	**Total Cost ($)**	**Cost per Pallet ($)**
Average	6.74	70.3	568,320	548.24
Std. Dev.	1.72	21.3	204,292	204.722
Truck	**Time (Days)**	**Op. Availability (%)**	**Total Cost ($)**	**Cost per Pallet ($)**
Average	91.19	33.38	200,233,602.50	200,192.60
Std. Dev.	7.968	5.7	59,000.06	59.147

The results show that helicopters are the fastest vehicles capable of delivering 1,000 pallets in the shortest amount of time. Helicopters also show to be the option that is available most often, followed by boats and then trucks. When cost is taken into account, it can be observed that the cheapest option results in the boats, followed by helicopters and trucks. Helicopters appear to be the best option, being mostly hindered by the cost.

2.2. Performance Gap/Problem Statement

The target performance was derived from the requirement to deliver 10,000 pallets within 90 days with a minimum 95% success rate, which corresponds to a minimum throughput of 111.1 pallets per day to sustain a population of approximately 70,000 people. The target cost was calculated to be under $400 per pallet. Trucks fail to meet all three metrics due to extremely slow delivery times, low throughput, and excessive costs. The ferry vessel on average delivers four less pallets per day than required and fails to meet the success rate by 60%. The helicopter surpasses the target cost by 40 dollars. These gaps demonstrate that no method simultaneously satisfies the operational requirements for time, cost, and throughput. In Table 4, the presented metrics are derived from 1,000 replications of the as-is process simulation model.

Table 4. Performance Gap (10,000 Pallets, 3 Vehicles)

Alternate Methods	Probability of 10,000 pallets in 90 days	Average Cost/Pallet
Trucks on Floating Causeway	0%	$20,218.89
Helicopters	100%	$449.92
Surface ships	35.18%	$283.25
Target	95%	$400

3. Analysis

3.1. CONOPS

Heavy-lift electric drones have the potential to deliver 10,000 pallets in 90 days with a 100% probability. This is feasible when electric power is provided by the AFPSL and CAS. The CAS includes a pantograph and power line (Figure 1). For application of the ship-to-shore use case, the power must be provided by a generator on a cargo ship.

Figure 1: Ship-to-Shore Electric Heavy-Lift Drones

3.2 To Be Process & Simulation

The To-Be humanitarian aid delivery process simplifies the current system by reducing the workflow from 20 operational steps to 10 and consolidating 12 actors down to 4 key actors: NGOs, engineers, contractors, and affected citizens. Once a humanitarian crisis is identified, NGOs coordinate logistics and charter cargo ships carrying aid to the affected region. Engineers then deploy the AFSPL system after confirming safe weather conditions. Contractors load aid onto heavy-lift drones, which travel along the powered catenary line from ship to shore, enabling continuous and efficient delivery of supplies. Multiple drones operate in a managed queue to maintain steady throughput while weather conditions are periodically monitored to ensure safe operations. Once supplies reach shore, contractors unload and distribute aid to inland centers for affected citizens. By consolidating actors and streamlining the delivery sequence, the To-Be process creates a faster, more reliable, and scalable method for ship-to-shore humanitarian aid delivery.

The simulation model used for the TO-BE process is the same as the one from the AS-IS process. It will use the same assumptions and perform the same tasks. The parameters of the helicopter can be assumed to be the same as the parameters for the drone except for the time to refuel, as the drone draws continuous power from the AFSPL. Drone cost parameters were derived from helicopter operational cost estimates, adjusted to remove fuel expenditure. The simulation assumes no drone downtime for maintenance; this represents a best-case scenario and is acknowledged as a limitation, as sustained 90-day operations would realistically require periodic maintenance windows.

Table 5: Drone Simulation Results

Drone	Time (Days)	Op. Availability (%)	Total Cost ($)	Cost per Pallet ($)
Average	9.82	68	234,800	234.8
Std. Dev.	2.505	17.4	65,000	65.052

The results show that drones manage to meet or exceed the previously defined performance metrics.

3.3 Requirements

The mission requirements define what the AFSPL must achieve in the field. They set clear targets for performance, safety, and operability so the system can support reliable ship-to-shore humanitarian aid delivery. Requirements were derived through stakeholder analysis, operational context review, and performance gap findings established in Section 2.

Table 6: Mission Requirements

ID	Name	Description
MR1	**Buoy Speed**	The AFSPL shall have a top speed of 5 MPH (8 KPH).
MR2	**Station Keeping**	The AFSPL shall maintain its designated geographic position within ±10 m horizontal under sea conditions up to sea-state level 5 (wind 17–21 kt, wave height 2–3 m) for a continuous period of up to 12 hours without human intervention beyond monitoring.
MR3	**Modular Packing**	The AFSPL shall be designed and packed into 4 individual modules, each sized and configured for handling standard shipboard cranes and a single 20-ton forklift or equivalent. Interface connectors shall be standardized for rapid mechanical and electrical join-ups.

3.4 Functional Architecture and Design of the AFPSL

The components of the AFSPL include the power pole, cross arm, floating base, and thruster/motor which work together to maintain the position of the catenary power line during ship-to-shore operations. The power pole provides structural support for the catenary wire at a height of 5 meters. The cross arm distributes lateral load from the wire tension. The floating base provides buoyancy and houses the onboard computer and solar panel unit. The thruster/motor assembly provides the propulsive force commanded by the station-keeping control system as shown in (Figure 2).

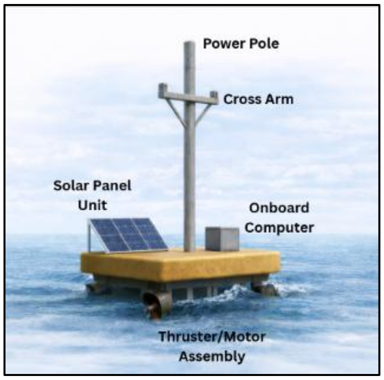

Figure 2: Station-Keeping Platform

3.5 PID Station-Keeping Control Simulation

The design of the PID controller for the AFSPL was modeled in MATLAB with 3 degrees of freedom being surge, sway, and yaw dynamics of a single vessel. The controller was tuned to minimize steady-state error and overshoot under dynamic ocean conditions, with thruster force saturated at 500 Newtons to reflect realistic hardware constraints. It evaluates sea-state level 3 conditions with a 5-mile deployment distance and zero initial velocity. Key findings showed 500 Newton saturation allows a 2-hour deployment window with a 20.78 kilowatt-hour battery requirement, 3.81-kilowatt maximum input power, 1.33-kilowatt average station-keeping power, 21 kilowatt-hour battery capacity for 12-hour missions, and approximately a 10-minute deployment time from 500 meters.

Table 7: PID Simulation Results

0.3 Miles Out	**x**	**y**	**Psi (heading)**
Settling Time (2% criterion)	680.83s (11.34 mins) (1.64mph)	205.84 s (3.43 mins)	242.50 s (4.041 mins)
Steady State Error (%)	1.12%	0.34%	2.26%
Overshoot (%)	1.47%	1.35%	22.87%
5 Miles Out	**x**	**y**	**Psi (heading)**
Settling Time (2% criterion)	4273.92s (71.23 mins) (4.18mph)	205.84 s (3.43 mins)	242.50 s (4.041 mins)
Steady State Error (%)	0.09%	0.34%	2.26%
Overshoot (%)	0.10%	1.35%	22.87%

3.6 AFPSL Deployment Methodologies

Fleet deployment methodology simulations evaluated 3 deployment strategies: Accordion, Ship-to-Shore, and Bidirectional approaches. The Accordion deployment deploys all AFSPL platforms simultaneously in a staging area and then expands outwards to their designated locations. The Ship-to-Shore method deploys AFSPLs in sequential order from the ship to the shoreline. The Bidirectional deployment method is like the Ship-to-Shore method but splits the platforms into two teams: one ship team and one shore team with two dedicated connection platforms that meet in the middle to connect the ship-to-shore power line. Each strategy was evaluated across four metrics: final position error, deployment time, energy consumption, and accuracy.

Table 8: AFSPL Fleet Deployment Methodologies Results

Method	Accuracy	Tension	Energy	Speed	Total Utility
Accordion	0.11	0.02	0.06	0.23	0.42
Ship-to-Shore	0.34	0.00	0.00	0.00	0.34
Bidirectional	0.00	0.00	0.06	0.30	0.36

Simulation results indicate that the Bidirectional approach achieves the shortest deployment time and lowest energy consumption by parallelizing deployment from both ends simultaneously. The Accordion method produces a high position error due to simultaneous multi-platform drift during the expansion phase. The Ship-to-Shore method offers a balance between position accuracy and energy use but is slower than the Bidirectional approach. Based on these results, the Accordion deployment strategy is recommended as the preferred method for operational use, offering the best tradeoff between speed, energy efficiency, and position accuracy. The Bidirectional approach would be preferred should the deployment speed of the AFSPL become a top priority in any given situation.

4. Business Plan and Conclusions

4.1 Business Plan

The business plan is to target humanitarian organizations including The World Food Programme, IFRC, UNHCR, and other disaster relief organizations. These organizations spend $60-110M on port denied ship-to-shore logistics annually. The AFSPL is a fee-for-service system, billed to customers on a per pallet cost basis. The AFSPL provides a ship-to-shore delivery service for $400/pallet. A conservative market capture assumes 2 humanitarian missions per year, delivering 10,000 pallets/mission. This assumption results in a 302% ROI, with a breakeven point in 3.5 years.

4.2 Conclusions

The destruction of piers and other shore equipment has made organizations seek to provide ship-to-shore logistics. The current alternatives used in logistics over the shore are helpful but are shown to have several performance gaps given the technology available. Drones could help relieve the performance gaps; however, the drones must work in tandem with the AFSPL. With the AFSPL, the drones are capable of delivering 10,000 pallets within the desired timeframe of 90 days. Stochastic simulations validated drone performance against throughput, cost, and mission success rate. A 3-DOF PID controller was designed and validated in MATLAB, confirming station-keeping feasibility under sea-state level 3 conditions. Three deployment strategies were evaluated, with the Bidirectional approach identified as optimal. Further steps were taken to find out the possible ways to move the AFSPL from the ship to shore, and feasible methods have been developed to make future proof of concept.

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