Conceptual Design of a Submersible Tactical Insertion Aircraft

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As part of the senior design program at Auburn University, the creation of a conceptual design for a submersible airplane is being undertaken as a response in part to a challenge by the Defense Advanced Research Projects Agency (DARPA). The design is expected to be a clandestine, coastal insertion vehicle with specific abilities of an airplane, surface ship, and submarine vessel, which would greatly increase the tactical ability of the United States. The aircraft is expected to accommodate eight passengers, including any necessary equipment operators, and an additional 2,000 pounds of cargo, and also to have an unrefueled range of 1,000 nautical miles in cruise flight, 200 nautical miles surface transit or very low altitude flight, and 24 nautical miles of submerged travel. The aircraft requirements also include the ability to complete one tactical transit (1,000 nautical miles airborne, 100 nautical miles surface, and 12 nautical miles subsurface movement) in a time limit of eight hours. This concept also addresses challenges in the areas of structural design, effective propulsion in dual fluid flow regimes, and control surface duality.

Nomenclature

CG = center of gravity
lb = pound, unit of force
nm = nautical mile, unit of length

I. Introduction

THE concept of human flight was ridiculed, and at the same time dreamed of, until it was proven feasible and undertaken by those intelligent enough and brave enough to do so. Likewise, prior to the 17th century, passage of seas under the surface was considered nearly impossible without the use of some mysterious magic. In the 21st century, civilization has become accustomed to seeing strange-looking boats sink under the water surface and reappear elsewhere, while the roar of jet engines is heard from a nearby airport.

The design undertaken at Auburn University seeks to unify the two disciplines mentioned: those of flight and undersea motion. Living on a planet which has a surface largely covered by water, it is natural for humans to have created aircraft which can call the surface of the water home, or at least a stopping point, but until now airplanes have been restricted from submerging due to their nature of low weight and designs set to make leaving the water surface or land easier. There exist numerous military applications of such a craft, and for this reason DARPA is looking to the engineering community to create a design answering the questions which must be addressed in order to make something designed to fly, sink. After all, the mission of DARPA is generally to protect the superiority of the U.S. military in the area of new technologies and prevent technological surprise, and what better way to prevent this surprise than to create it for our adversaries?

In order to complete the design program at Auburn University, this challenge has been undertaken in the form of a conceptual design seeking to deploy operators at a seashore in as undetectable a manner possible. The design was begun in the form of consideration regarding what type of airplane could possibly survive going under the water surface, what propulsion system, or systems, would be required, how the passengers would be accommodated, and more. Once the ideas were formed, they were compared and mixed to a degree such that an aircraft only partially impossible began to take shape. From that point, a commonplace program of initial analysis and computation was used to modify the design into a feasible form.

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II. Design Requirements and Background

In the broad agency announcement issued initially in October of 2008, DARPA warned eager participants in the program that, “Prior attempts to demonstrate a vehicle with the maneuverability of both a submersible and an aircraft…have been unsuccessful largely because the design requirements for a submersible and an aircraft are diametrically opposed.”[1] Thus it was known that in order for a group of university students to achieve a promising design, the requirements and challenges first needed to be fully understood.

The purpose of a craft such as the one for which designs were solicited was to have a vehicle which had three very desirable qualities: “1) the speed and range of an aircraft; 2) the loiter capabilities of a boat; and 3) the stealth of a submarine.”[1] For this mission, the airplane was required to take off and land both from terrestrial bases and the water surface, and also to submerge. The specification for what depth the vehicle must submerge to was not set other than to require the entire fuselage, with the exception of any snorkel equipment needed, to be completely under the surface.

The passenger and cargo handling capability was also subject to a design requirement. A successful design was to have the ability to accommodate 8 passengers, also known as operators, at an unspecified weight, as well as 2000 pounds of additional cargo. For use with the conceptual design, a maximum weight threshold of 250 pounds per operator was set. The number of passengers included any number of pilots required, whether for flight or submersible operation. In addition, all passengers and cargo were required to be contained in one continuous volume.

As with all vehicles, the distance and speed of travel were major considerations with this concept. The total range of the aircraft, without refueling, was set to 1224 nautical miles: 1000 of the miles were to be completed in cruise flight, 200 in very low-level flight or surface transit, and 24 below the surface. Of the range, 1112 nm (1000 nm of cruise flight, 100 nm of very low-level flight or surface transit, and 12 nm of underwater movement) were to be completed within at most eight hours. The designed aircraft was also required to be able to sustain operational ability during and after a three-day long loiter period to occur on or under the water surface in the midst of the mission, after the 1112 nautical mile mission segment was complete.

For successful completion of the mission, the design was completed with four primary challenges in mind: effective propulsion above and below water, duality of control surfaces in different fluids, the method of landing and takeoff from water, and the weight of the vehicle. It was determined early in the design process that for the proposed vehicle to be considered feasible, it must acknowledge each of these issues and satisfy them in turn.

III. Concept

As opposed to prior attempts at creating submersible aircraft (which were essentially submersibles with appended wings and flight control systems), the current concept was created from the angle of designing a flying machine, which could then be conceptually modified to also operate underwater.

For this reason, the design took shape around a very airplane-specific subject: landing and taking off. For the problem at hand, the landing and takeoff configuration(s) were required to withstand both land and water touchdowns. A unique takeoff and landing system of two configurations was devised, one for land and one for sea. For terrestrial operation, it was decided that a standard tripod design would suffice, and due to its widespread and proven use it would also keep the design simple. The sea-based configuration was a new concept designed specifically for this application; it featured a system of buoyant tanks, or pontoons, which would be the only surface in contact with the water during landing or takeoff. The system was also conceptualized as a tripod, with one hydrodynamically optimized pontoon to deploy from the forward fuselage section, and two others, integrated into the wingtips. For landing, the outermost seven feet of the wingspan on either side would fold downward upon a hinge in the wing, thus positioning the pontoons below the bottom surface of the fuselage. This landing concept was preferable in that it raised any propulsion system inlets a significant distance above the water surface, prevented the fuselage from being designed as a heavy vessel-type hull, and because it was believed that upon touchdown the large pontoons would create static stability on the surface.

In tandem with the takeoff and landing configurations, a novel propulsion model was developed for use in both air and sea. In order to reduce weight and the need for large stores of batteries, it was decided that a single propulsion system would power the craft. The concept of a turbofan engine was adapted to the needs of the design in the form of a turboshaft engine connected to a set of integrally bladed rotors, or blisks, as part of a ducted fan. For underwater performance, the engine was to have access to an oxidizer via a snorkel rising above the surface of the water, while the ducted fan would propel the craft by driving water in the place of air. In order to accomplish the transition from air to water operation for the fan, while keeping acceptable performance, it was proposed that a mechanical transmission be installed between the turboshaft engine and the fan, in order to step down the rotation rate of the fan blades and prevent cavitation of the fluid.

For successful integration of the landing and propulsion concepts, a mid-low aspect ratio was chosen for the main wing. This was for general structural stability when encountering the higher density and viscosity of seawater, and also to enable the wing to be thicker to incorporate structural support mechanisms primarily for use with the folding-wing landing concept.

Having a general idea of what the craft would look like and how it would operate in flight, the task of making it operate well underwater necessitated some modifications to the concept. In order to pull the nose under the water level and provide a downward thrust vector, an all-moving, symmetric canard which could be deflected large negative angles was used in place of a conventional tail. Also, to reduce the enormous amount of buoyancy within the airframe and fuselage, the concept was modified to house a "wet" interior, where only certain portions such as that immediately surrounding the engine, would be isolated from water, and all else, including the passenger cabin, was to be flooded. Also, all-moving horizontal dive planes were added to the wingtip pontoons which would contact the water and provide downforce upon landing and retraction of the forward pontoon.

During analysis of the design concept, it was discovered that there was a fundamental flaw in the water landing plan and equipment. Due to the torque produced by the wing-mounted pontoons upon contact with the water surface, the axial twisting of the wings produced a hazard to the structure and the occupants. To prevent this, the folding-wing landing was abandoned, and a new concept designed. To replace the downward force produced by the former dive planes on the wingtip pontoons, a set of hinged dive planes were to be stowed in the fuselage during flight and deployed in order to aid submersion. It was decided that the undercarriage of the fuselage would be able to best withstand the impact of landing if braced correctly. The fuselage was redesigned to include a seaplane hull with a tapered rear profile. The lower surface of the rear fuselage was sloped upward with an included step to accommodate planning of the hull during takeoff and landing on a smaller surface area; the slope was also required in able to raise the nose of the aircraft such that the low-mounted canard would clear the water surface and thus be an effective control surface during the transition. In order to assist in raising the canard above the water surface, a deployable ski, able to produce only hydrodynamic lift was put in place of the front most pontoon. Thus, the SAILFISH, or Submersible AIrcraft Landing on Fuselage and hydrodynamic Ski, was conceived.

IV. Propulsion System

Due to the fact that the propulsion system planned for use with the SAILFISH concept will encounter two drastically different fluid mediums, it was initially though to be a simpler solution to incorporate two separate propulsion systems, one for flight and one for submerged transit. However, it was found that only air breathing engines carry the power density feasible for flight since a major portion of the fuel is stored in the air as oxidizer. A simple order of magnitude analysis of power density of applicable batteries revealed that the submersible aircraft concept would have to carry an amount of batteries approximately equal in weight to the initial empty weight estimation of the craft without them to supply enough energy for the short 24 nm undersea voyage. For this reason, an air breathing engine was found to be closer to the ideal propulsive system, as long as there was an air source.

With the design consideration shifted to types of air breathing propulsion, different conceptual systems were studied. Turbojets offered outstanding thrust with moderate fuel consumption, but their functional ability in a submerged state was doubtful due to the nature of the water medium which would surround them and produce backpressure on the nozzle(s). Unducted fans, studied by the National Aeronautics and Space Administration and the aircraft industry in the 1970s and 1980s, were also considered for a means of propulsion. This ultra-high bypass engine offered moderate thrust with low fuel consumption, and could have perhaps provided a single engine system for both aerial and submerged performance, but in the air-to-sea transfer a complete engine shutdown would be inevitable to prevent blade damage or destruction upon contact with the water surface.

A single engine system with a propulsion unit optimized for air transit and acceptable efficiency in a submerged environment, which would provide a seamless integration between the two contending concepts, finally became the choice of the design team. A gas turbine in the form of a turboshaft engine will power a large-diameter ducted fan via a geared transmission for all modes of transportation. The engine was considered "rubber" for the conceptual design of this craft, although commercially available models were used for fuel consumption estimation. The fan section is planned to be comprised of a set of contra-rotating integrally bladed rotors, or "blisks", for reasons of lower fluid drag in the area of intersection between the blades and housings and also for dependability in high-stress situations, such as when the fluid propulsive medium has a higher-than-normal density. Both elements, the engine and fan, will have separate intake and duct systems.

In the case of water landing, the transmission will be clutched once the craft is stationary on the surface as secondary fan intakes on the bottom of the fuselage open, and the primary intakes, housed higher on the fuselage, close. Once these lower intakes have opened, the ducted fan will again engage, at a lower rotation rate than that used for flight, to ingest and expel sea water, producing thrust. The air intake for the engine is in the form of a snorkel 30 feet long. The snorkel was positioned on the centerline of the fuselage top, above the high wing and lower canard, in order to minimize water introduction. While submerged, it will be deployed in order for proper air ingestion. Exhaust gases from the power plant will also be projected up through the snorkel, in order to minimize the flash-boiling of water at the exhaust exit, therefore reducing our "bubble trail".

V. Structure

A. Fuselage Exterior

Designing a submersible aircraft requires a supporting structure lightweight enough to fly, but which is still able to resist the pressure gradient experienced beneath the surface of the water. Thus, the skin must be a compromise between that of a submarine and aircraft. The skin of many aircraft is made from aluminum or composite materials while the hulls of submarines are typically built from high strength steel. Since DARPA required that the aircraft be able to fly more than 1000 nm, a skin made from steel would prove far too costly in weight and the propulsion system required to lift such a heavy body into the air. Also, it was decided that in order to make easier the task of submerging, the aircraft interior will be "wet", or flooded, while submerged, and as a result the turbine is the only component which must be completely sealed from the water. Thus, an aluminum skin thicker than that normally used on similarly sized aircraft was deemed acceptable. Corrosion issues were also considered, but they are not believed to be a major issue with the aluminum alloys and coatings used today, and therefore the concerns were considered for this conceptual design phase to be negligible.

The SAILFISH required a structurally feasible hull which could support the full loading upon impact with the sea, and also one which would reduce the surface drag in such a way to make water takeoff possible. For this reason, a seaplane-type hull was selected as the bottom fuselage surface. The hull was designed with the classic “V-shape” in order to decrease the direct load seen upon impact. The height of the hull was found along with the angle of the side of the V-shape measured in degrees upwards from horizontal, also known as the deadrise angle α, using Equation (1), which is a function simply of V, the stall speed.[3]

$$\alpha = \frac{V}{2} - 10 \tag{1}$$

Towards the rear of the beam of the V-shape hull, a break in the keel line, or step, was incorporated. This step will reduce porpoising tendencies and will make the aircraft more stable during take-off, landing, and any surface transit encompassed in its mission. In sea planes, the fuselage normally angles upwards at the step about eight degrees. The upwards slope of the rear of the fuselage conveniently corresponds to how conventional land based aircraft usually have upwards slope in their empennage that tapers the fuselage and elevates the tail control surfaces. This application utilizes a higher-than-normal slope in the rear to raise the low-mounted canard and nose of the airplane during landing and takeoff in order to save the surfaces from impact with the sea. This will affect the range of flare the aircraft can undergo during ground landing, but should suffice for both land and carrier based take-off by allowing enough tip-back angle.

B. Turbine Intake System

The propulsion system on our aircraft requires a snorkel system to deliver air to the engine and also to route the exhaust gases into the atmosphere while submerged. The snorkel interior will be divided in two halves along the length. The rearward half will act as the turboshaft intake while in flight and submerged while the forward half will act to exhaust the spent gases of the turbine while the aircraft is submerged. Due to possibly drawing spent gases into the intake, the snorkel exhaust portion will be approximately three feet shorter than the intake side. While the aircraft is in flight the snorkel acts as the air intake for the turbine, but the exhaust gases are diverted through a nozzle at the tail end of the aircraft. The snorkel stretches almost half the length of the fuselage from the cockpit to a joint approximately 30 feet to the rear. Because the snorkel is relatively long, it will create sizable drag when raised. As such, the cross-section is elliptical with the semi-major axis parallel to the fuselage of the aircraft. In order to properly stow the apparatus during flight, the top of the craft fuselage is designed to securely fit half of the snorkel below the perimeter of the skin during flight, thus only introducing the intake half into the freestream and reducing aerodynamic drag. To protect against engine hydrostatic lock a system was conceived to sense a surge of water in the intake, seal the snorkel five feet from the top and open a port just above the sealed section to allow the water to exit the snorkel. Immediately after the water has exited the snorkel the port will reseal and the closed section will reopen to allow continued flow of air into the turbine.

The gas turbine is sealed within a fully enclosed pressure vessel to further prevent any water from entering the engine. A clamshell-shaped device will deploy just aft of the turbine outlet to seal the exhaust side from water back pressure and to redirect the spent gases into the exhaust side of the snorkel.

C. Passenger and Cargo Cabin

DARPA required the aircraft to be capable of carrying 8 operators in addition to 2000 lb of cargo or equipment. To accommodate this, the design of the compartment allows modular storage of cargo and seating of passengers. Storage blocks are split up into sections with an area of four square feet to allow an arrangement of cargo and passengers suitable for each mission and enable proper weight balancing if necessary. The dimensions are 25 feet long, 7 feet wide, and 5 feet tall. The passenger compartment will be wet to eliminate the extra weight that would be required to seal and pressurize it.

VI. Landing and Takeoff Configurations

One requirement set by DARPA was that the submersible aircraft should be able to take off and land from a land base. Since this vehicle is for covert insertion, it would also be beneficial to have it available on station around the world. The result is that the decision was made by the design team to make the landing gear also suitable for aircraft carrier takeoff and landing. This meant that certain guidelines concerning the United States Navy's equipment were to be followed. Some examples are the stipulation that the nose gear must have tires of at least 19 inches in diameter, that the "tip-back angle" exceeds 25 degrees so that the center of gravity for the aircraft is far forward of the main wheels, and that the "overturn angle" can be no greater than 54 degrees. Although landing gear in and of itself will not greatly influence the conceptual design, it will allow for more accurate general sizing and weight estimates of the aircraft as carrier-based landing gear is substantially heavier than conventional landing gear.

Another obvious consideration taken into account stems from the mission of the submersible aircraft. The mission profile stages contact with a body of water, mainly open ocean in sea state five. Two major issues were how the aircraft would land on the water and maintain stability in ten foot swells and the associated high wind speeds. It was decided that the aircraft would land on the fuselage for this reason. The fuselage-turned-hull is tapered according to projected landing speed so that it will survive landing.

With regards to stability on the surface, most sea planes include pontoons, mounted below the main wing on struts, in the design. This aircraft is no exception, especially since it will be experiencing wave activity in sea state five. Unfortunately this will produce awkward pitching moments in flight and in underwater operations, but these are issues that are dealt with in the control systems which are necessary for such an exceptional design.

Using methods described in Reference 3 and coded in MATLAB, in conjunction with initial sizing geometry, calculations regarding landing and takeoff on both land and sea were made, including obstacles measured at 50 feet. For sea conditions, the takeoff distance was found to be 2,459 feet, and the landing distance was 2,406 feet. For land-based maneuvers, the takeoff distance was calculated as 2,092 feet, and the landing distance was also approximately 2,406 feet.

VII. Aircraft Sizing

Conceptual sizing for a new aircraft usually concludes by comparing similar aircraft that have already been produced. For the design of this vehicle, values were used from water landing capable aircraft. The initial sizing for total needed lifting area was based on the sea level stall speed, assumed maximum lift coefficient, and the estimated gross weight from estimating fuel-fractions.

The initial quarter chord sweep angle, aspect ratio, and taper ratio were chosen to maximize lift, reduce wing structural complexity due to

Table 1. Design specifications.

	Design Requirement
Minimum/Stall Speed	60 knots
CL MAX	1.5
Estimated Gross Weight	40628 lb

the expected forces associated with the craft being submersed, and chosen along a historical trend respectively.

The initial canard sizing was based on setting a certain percentage of the total lifting surface area as the canard. The fraction used, 0.24, was slightly higher than shown in historical trends because of its duality as an underwater control surface.

Table 2. Main wing and canard specifications.

	Wing	Canard
Quarter-Chord Sweep Angle	0 deg	0 deg
Aspect Ratio	3	4
Taper Ratio	0.6	0.5

The vertical stabilizer sizing was based on the method in Reference 3. This method uses typical historical values to estimate the volume of the stabilizer based on the wing area.

The driving input for the fuselage length were the root chords of the main wing and canard, the crew/cargo compartment, and the estimated length of the propulsion system. The passenger and cargo compartment sizing incorporated an interchangeable modular design. Each operator was allotted 250 lb. The cargo was also split into eight 250 lb sections. Two of the eight operators reside on the flight deck and control the aircraft while the other six are located in the passenger and cargo compartment directly behind the flight deck. In the passenger and cargo compartment each module space, six for operators and eight for cargo, were laid out to ensure the best trade-off between operator comfort and efficiency of the design. The modular design allows for the layout of the cargo and operators to be reconfigured if the need arises.

Table 3. Calculated initial sizing values.

	Reference Area (ft^2)	Exposed Area (ft^2)	Span (ft)	Root Chord Length (ft)	Mean Aerodynamic Chord Length (ft)
Wing	1688.9	1454.3	71.18	29.66	24.22
Canard	533.35	533.35	46.18	15.39	11.97
Vertical Stabilizer	534.32	534.32	15.5*	26.5	18.89

The control surface sizing was based on the method from Reference 3. This method takes historic relationships between the reference area and the control surface area. The area of the elevators can be seen as calculated in Table 4.

Table 4. Control surface sizing information.

	% Span	% Chord length	Root Chord length (ft)	MAC length (ft)	Control surface area (ft^2)
Ailerons	60	20	5.931	4.844	206.9
Rudder	90	32	8.482	6.046	168.7

VIII. Weight

For a craft intended for flight, weight plays a large role in success or failure. In this case, weight is even more important, as it must be balanced between the extremes of flying and sinking vehicles. Many specific methods for estimating group and specific weights are documented and available; for this initial weight analysis, a number of methods were utilized and averaged. The algorithms used were calculated as found in Reference 2.

D. Structure Weight

The structure weight estimation was computed by first individually estimating the weights of the wing, empennage, fuselage, the nacelle, and landing gear. In this case, the nacelle weight referred to special ducting configurations other than the buried-engine inlet duct, which includes the snorkel. The calculated structure group weight was 16,770.01 lb.

E. Powerplant Weight

Powerplant weight estimation was completed by first individually estimating the weights of the engine, air induction system, fuel system, and the propulsion support systems. The air induction system refers to the inlet ducting and any duct support structures, and the propulsion support systems include the engine control system, the engine starting system, and the weight of any oil system or oil coolers. The calculated structure group weight was 4,447.30 lb.

F. Fixed Equipment Weight

The weight estimation for fixed equipment was computed by estimating the weights of the flight control system, hydraulic system, electrical system, electronics systems, air conditioning and de-icing systems, oxygen system, APU, and furnishings. Also included is cargo handling equipment, operational items, auxiliary gear, and paint weights. In addition to the usual items, a pump weight for evacuation of water from the fuselage upon surfacing was also included. The calculated structure group weight was 5,780.73 lb.

G. Estimated Empty and Gross Weights

The compiled empty weight, along with the estimated fuel weight and all payload, was used to generate an initial gross weight estimation. After a number of iterations through the process of adjusting the gross weight, empty weight, and aircraft sizing values, the estimated empty weight was found to be 27,293.72 lb, and the corresponding takeoff gross weight was approximated as 40,628.50 lb. As with all conceptual design, these values are destined to change, but are both workable approximations.

H. Center of Gravity

Using approximated distances found with the use of to-scale structure and propulsion system designs, a center of gravity, or CG, location was found on the aircraft. This location was found to be at 31.1 feet from the nose for the case of no fuel and no payload on board, and at 33.5 feet for the case of full fuel and payload.

IX. Aerodynamic Properties

Given the challenge of working with two distinctly different fluid regimes, the subject of “aerodynamics” is not only of flying in air but flying in both air and water, thus making the problem one of fluid dynamics.

As an initial baseline to start the design process, the NACA 0012 was selected for the canard. For the main wing, the NACA 23012 was selected due to its high lift and low pitching moment characteristics in the NACA five digit series. Traditionally, designers and engineers have been afraid of this airfoil due to its violent stall characteristics. The submersible aircraft being a canard design should qualm those fears because typically the canard will stall before the main wing thus nosing the aircraft downwards, breaking the stall and thus leading the aircraft back to safe flight. In regards to submerging the aircraft, the obvious result of the cambered airfoil is the inability to submerge due to this huge main wing lifting surface. As a remedy, the thought is to incorporate leading edge flaps much like what is found on transport aircraft, but rather than the flap increasing the camber of the wing, it deforms in such a way to produce a negative camber. In addition, much like the leading edge flaps, the trailing edge flaps would act in tandem and possibly deliver a negatively cambered airfoil capable of meeting the negative lift requirements for submerged flight in conjunction with the smaller, symmetrical canard.

Initial calculations of the neutral point and CG locations showed that the aircraft has a sensitive static margin. Relocation of subsystems is possible in order to increase the static margin. The CG envelope, which incorporates an initially calculated neutral point for the aircraft, can be seen in Fig. 1.

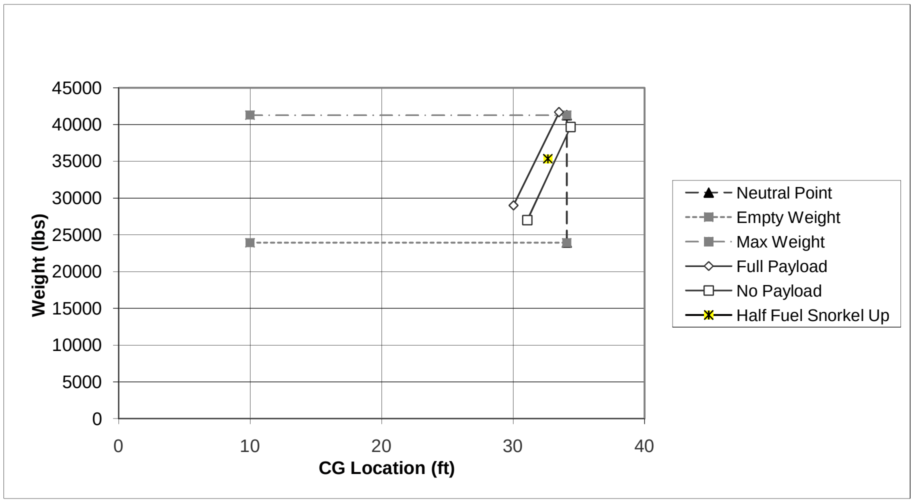

Figure 1. CG envelope shown with neutral point boundary.

X. Conclusion

The concept of a submersible airplane requires a broadening of the capabilities of flight. An aircraft capable of flying thousands of feet in the air and hundreds of feet under water must be able to operate efficiently in a variety of conditions. This required a new design for the propulsion system, a way to safely land and then submerge in seawater, and a design that would work well aerodynamically, in a variety of fluids. As described above, the SAILPLANE blends all of these together and meets all of the requirements and provides the DARPA project with the most safe and efficient airplane possible.

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