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SUBMERSIBLE SEAPLANES AS THE PATH TO HYBRID FLYING AND DIVING CRAFT

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SUMMARY

A survey of novel hybrid unmanned aquatic–aerial vehicles in 2015 proposed the term 'AquaUAV' and overviewed developments in both seaplane UAVs and a new class of submersible UAVs that can dive. The submersible developments by Beihang and Nanchang Hangkong universities a decade ago have led to morphing and copter AquaUAVs. An Australian university research team have conceptually designed a submersible seaplane that merges the maturity of the seaplane class with covert underwater insertion, travel and recovery. The reconnaissance design inserts from underwater emplacement, surfaces, can fly in ground effect, keeps station on the sea surface while recharging, travels and wait for collection underwater. The design minimizes doppler and infra-red signatures to evade the surface-wave and backscatter radar systems and cube-satellite arrays typical in contested maritime areas. Five critical enabling technologies are overviewed, showing how they enable the design. The university is hoping for sponsorship for prototype testing.

Keywords: aquatic unmanned aerial vehicle, submersible seaplane, wing in-ground effect, syntactic foam, computational fluid dynamics, solar recharge.

INTRODUCTION

Yang et al. (2015) provided a comprehensive survey of novel hybrid aquatic–aerial aircraft in 2015, proposing three classes of 'Aqua-UAV:' seaplanes, submarine-launched and a new class of submersible UAV that can dive. According to their survey, the AquaUAV developments by Beihang and Nanchang Hangkong Universities a decade ago have led to bio-inspired wing morphing and quadcopter AquaUAVs. Furthermore, they assessed that '*Solving the compatibility problem of the wing layout, hydrophobic material selection, pressure-resistance structure design and fabrication, fuselage shape, dynamic system, and weight in the air and the water, will be the most significant technical challenges for the AquaUAV to change from a conception to a practical prototype.*'

An Australian university research team have conceptually designed a submersible seaplane that merges the maturity of the seaplane class with covert underwater insertion, travel and recovery (Carroll et al., 2021: accepted). The reconnaissance design is shown with dimensions in Fig. 1) and is an estimated 27 kg. The craft missions are still evolving; however, it can insert contested areas with underwater emplacement, surfaces, fly in ground-effect, keep the station on the sea surface while recharging, and travel and wait for collection underwater. In addition, the design minimizes doppler and infra-red signatures to evade the surface-wave and backscatter radar systems and cube-satellite arrays typical in contested maritime areas (Joiner et al., 2019).

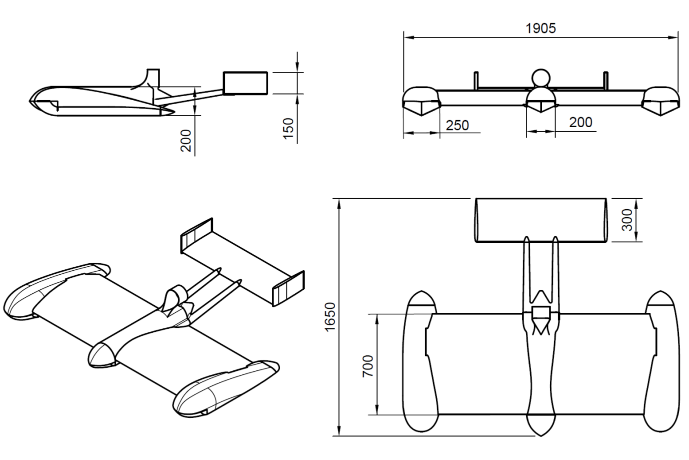

Fig.1. Overview of Australian Conceptual Design of a Submersible Seaplane.

Five of the leading enabling technologies are overviewed in this article to show how they enable the design:

- Wing in-ground effect for efficient high-endurance and low-speed cruise while staying very low to the water for reduced doppler signature.
- Electric ducted fans from the developing drone market are powerful enough for takeoff from water and efficient in both above and below water cruises.
- When merged with carbon fibre, new compressible syntactic foam materials can survive both depths, flying and landing forces.
- Enhanced batteries and conformal solar panel recharging technologies.
- Evolving computational fluid dynamics (CFD) packages can analyze biomimetic design features when immersed in and transiting air and water media.

The university is hoping for sponsorship for prototype testing its Low Observable Submersible Seaplane for Electronic Intelligence (LOSSEI, pronounced 'Low-Sea') in 2022-2023.

WING-IN-GROUND EFFECT

Ground effect, or WIG, is a natural phenomenon of improved aerodynamic performance to marine aircraft operating near the water surface. However, this effect is only evident when an aircraft is flying at a height less than the length of one wing chord (Yun et al., 2010), named by some researchers as the critical height (Nirooei, 2018).

The ground effect combines two aerodynamic phenomena: chord and span-dominated ground effect (Hiemcke, 1994). The chord-dominated ground effect increases the lift by developing an extremely high-pressure air cushion on the airfoil's underside as it approaches the ground (Ahmed et al., 2007). During WIG flight, the air on the wing's undersurface decelerates significantly, trapping the air between the ground and wing, increasing the pressure. This air cushion is also known as the ram effect and can cause the air under the wing to stagnate if the clearance height reduces too much.

Span-dominated ground effect directly influences the induced drag of the airfoil. The wingtip vortices cannot fully develop at low ground clearance, and therefore the leakage from the underside of the wing is lower (Yun et al., 2010). As a result, the dynamic cushion increases the effective span and the effective aspect ratio of an aircraft. The research documented by Qu et al. (2015) finds the WIG effect declines with reducing aspect ratio and that end-plates can retain the WIG effect for lower aspect ratios as used in our conceptual design.

Hiemcke (1994) found that the ground effect phenomenon is only significant if the wing is within one chord length of the ground plane. He showed that at a maximum, the lift is increased by approximately 66 per cent when the height-to-chord ratio is 0.1 compared to airfoil performance out of WIG. Values of height-to-chord less than 0.25 have been referred to as extreme ground effect, as these place aircraft at higher risk of impact and induce stability challenges (Nirooei, 2018).

The LOSSEI craft has been designed with a NACA 4412 airfoil because it has been used extensively for wing in ground-effect research (Hazenberg, 2020), albeit this airfoil has since had minor improvements for the WIG effect documented by Nirooei (2018). The air cushion trapped by the ground-effect is shown for the LOSSEI craft in Fig. 2 at a height-to-chord ratio of 0.1 or 70 mm above water and maximum endurance speed for this condition of 21 m/s.

Note that the outboard demi-hulls aid in the span-dominated ground effect and are shaped to cushion the landing and provide buoyancy for sea-keeping.

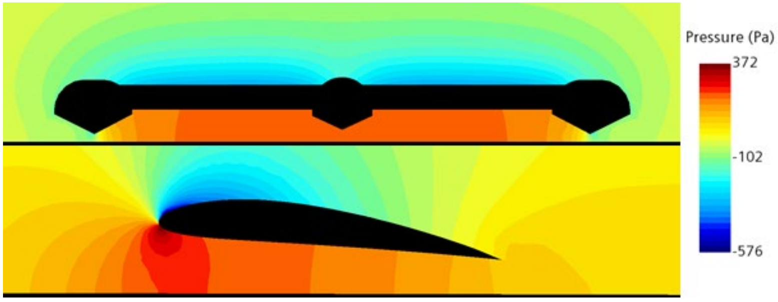

Fig. 2 CFD of the LOSSEI craft in-ground effect at the maximum endurance speed condition

In addition, the wing has a set-angle of four degrees to the fuselage and demi-hulls to aid in close ground effect and minimize rotation at takeoff.

Research into the stability of the NACA 4412 (Hao et al., 2013) and the effect of surface waves by Haode and Dongli (2020) has been extended by the Australian team, showing promise of the effect being sustained across waves, on average, and with manageable perturbations from the wavelengths using laser-ranging altimeters (Carroll et al., 2021: accepted).

ELECTRIC-DUCTED FANS (EDF)

The greatest challenge for the EDF is the takeoff case. Due to the hydrodynamic drag, the thrust required for LOSSEI to takeoff is significantly higher than that for a conventional UAV. The thrust required to takeoff from flat water is modeled in Star CCM+ at six positions with fixed velocity and pitch angles, shown smoothed in Fig 3. Lift on the LOSSEI craft throughout the takeoff cycle begins at low speed, being dominated by the buoyancy force. As velocity increases, lift is dominated by hydrodynamic lift as the fuselage and demi-hulls begin to plane on the water surface. The end of the takeoff sequence shows aerodynamic lift finally taking LOSSEI into the air.

Fig.3. Initial CFD data for LOSSEI's take-off thrust required compared to a chosen EDF thrust

The EDF for LOSSEI is intended to be an off-the-shelf unit. Therefore, an EDF that is likely to meet the thrust requirements of the LOSSEI system is the Schuebeler Technologies DS-215-DIA HST EDF, which has a maximum thrust of 250N at a weight of

3.4kg. The maximum thrust of this EDF is also shown in Fig 3.

Estimation of the thrust this can provide underwater is based upon blade element momentum theory, which follows experimental data for air designed propellers when operated underwater (Parth, 2016). A propeller can produce approx. 30 times more thrust in water than air and subsequently requires 30 times more torque at a given RPM. Therefore, maximum thrust in the air can be matched underwater at lower RPM. Furthermore, hall effect sensors allow a brushless motor to deliver high torque at low RPM as the speed controller no longer relies on back electromotive force (EMF).

COMPRESSIBLE AND TENSILE MATERIALS

The wing structure is a critical assembly that will undergo both hydrostatic and aerodynamic loads during the operation of the craft. As shown in Fig 4, the wing structure is designed for aerodynamic loading; however, it is designed to be filled up with water whilst submerged to avoid being crushed underwater. The syntactic foam (yellow/tan) is present in areas where the structure will experience relatively low tensile loads but will need to withstand hydrostatic loads. The carbon fibre (black) is present in areas that will experience torsion and bending loads that will be experienced in flight.

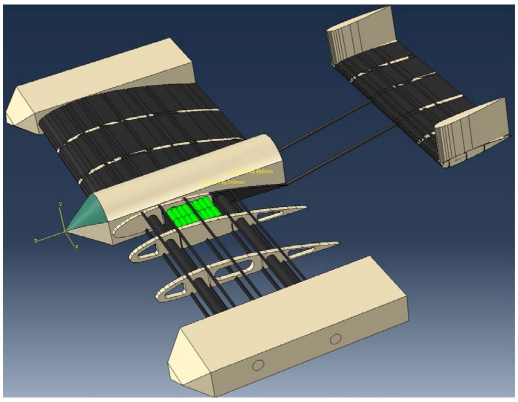

Fig.4. Wing material design considerations

Carbon fibre's lightweight and tensile properties have been researched and exploited for some time (Bhatt and Goe, 2017). However, for a seaplane to submerse requires lightweight compression strength. The material chosen is syntactic foam, as used in sea vehicles (Kingston, 2019). While the structural design has not yet achieved the target weight, the proximity of early estimates shows promise that refinement is likely viable.

BATTERY AND SOLAR RECHARGE

The battery system for LOSSEI is intended to be comprised of lithium-ion (li-ion) 21700 cells. Other cell options such as NiMH hydride were also considered for fire safety; however, NiMH's significant power draw during takeoff is insufficient. The Li-ion battery is split into four sections, each with a battery management system to reduce the chances of thermal runaway. Separation of the battery segments also assists in preventing chain failure, as one failed section is less likely to cause thermal runaway in the entire battery due to being separated by syntactic foam. The nose and centre fuselage sections are located within the fuselage pressure vessel. The wing sections will be waterproofed by a vacuum-sealed bag, filling any remaining airgaps with oil to prevent water ingress. This method is like conventional autonomous submarine battery packs. The total weight and capacity of LOSSEI's battery pack, using average li-ion 21700 cells, is estimated to be 18kg and 99Ah, respectively. The battery pack will deliver 425A to the EDF, which has a max current draw of 280A.

The battery system will be supplemented by solar augmentation. Solar panels on the wings allow for recharging of the battery system while not in flight, increasing the operational endurance of the craft. Detailed analysis of the effectiveness of this solar augmentation and mission profiles are overviewed in Carroll et al. (2021: accepted).

COMPUTATIONAL FLUID DYNAMICS

The design advantage of CFD in both air, underwater and transition has been illustrated already in the takeoff case shown in Fig. 3. Verification of these models involves careful mesh independence and time variance techniques. The takeoff case involves a balance of the hydrodynamic, aerodynamic and buoyancy forces in

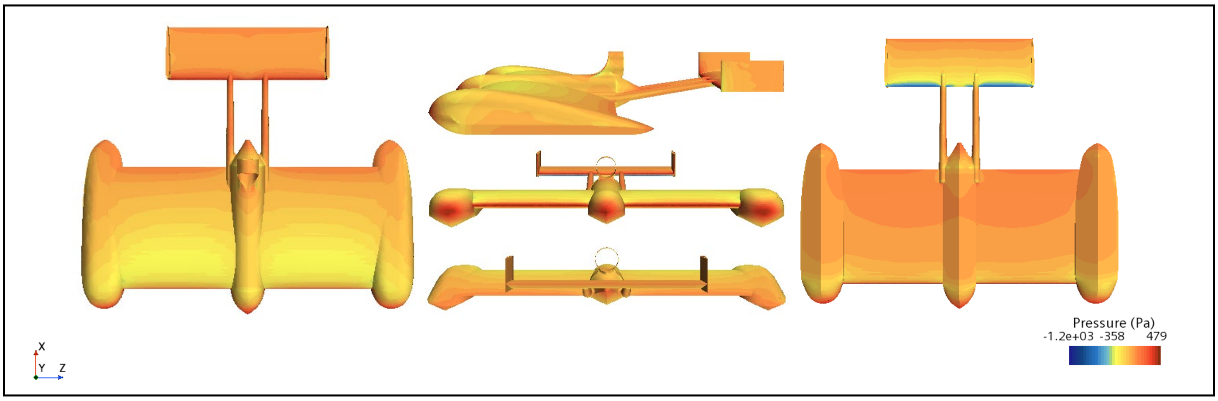

Fig. 5 CFD of Underwater Cruise Condition showing pressure contours

determining the vertical position of the craft in the water. The takeoff case can be validated by calculating the individual forces and comparing the height above the waterline. The team is also exploring a simulation to investigate the landing loads, building from work by Hunter (2021) and the updated geometry for the LOSSEI. Data from this simulation is to be utilized in the structural analysis of the craft. Experimental wind tunnel testing was used to validate the mesh and time steps for the above water models. The meshes were created to balance the accuracy of results whilst minimizing computational time.

A case to show the CFD work is the viability of the underwater cruise, where the pressure contours are shown for the maximum endurance speed condition of 1.83 knots (Fig. 5). Submerging and achieving neutral buoyancy at depth requires the craft to flood the demi-hulls and wing sections that do not store equipment. The underwater cruise case involves an analysis of the drag of the LOSSEI craft in both free-stream air and shallow underwater. This analysis allows the total drag and velocity to be compared to above water operations and estimate subsurface energy and thrust requirements.

CONCLUSIONS

A submersible seaplane has been conceptually designed by an Australian university that exploits developments across five key technologies to achieve viability. First, the use of wing in ground-effect has substantially improved endurance of flight, reduced power required and reduced detection compared to flight out of ground effect. Second, new electric ducted fan designs offer sufficient propulsion for takeoff and cruise while enabling limited underwater travel to aid insertion and recovery. Third, merging carbon fibre from aircraft with syntactic foam from undersea vessels provides strength in both domains. Fourth, the development of Lithium-Ion batteries provides sufficient power to take off and perform missions. At the same time, conformal solar technology allows recharge of the batteries while on listening stations during the day. Finally, advances in CFD enable designers to examine craft design features in air, water and across the transitions.

The conceptual design of a low-observable submersible seaplane for electronic intelligence is ready for detailed prototype design and testing.

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