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Concept and testing of an electromagnetic homing guidance system for autonomous underwater vehicles

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ABSTRACT

An effective homing guidance system with precise vehicle dynamic attitude control capability is essential for reliable docking of Autonomous Underwater Vehicles (AUV). The paper describes the bio-inspired concept and electromagnetic finite element analysis-aided design and testing of an electromagnetic homing guidance system (EMHGS) comprising of an underwater dock with 400AT of electromagnetic dipole coil excited with the 20 Hz power supply; a twin-thruster AUV equipped with a differential magnetometer system, and operable in two degrees of freedom (DOF). The vehicle hydrodynamic behavior is characterized in 2 DOFs based on the thruster action and vehicle response method, and used for the control and homing guidance of the AUV. By sensing a magnetic field strength of 190nT, the EMHGS is found to have an effective range of 7 m, and capable of effecting AUV orientation correction by measuring the bearing angle. The FEA is found to comply with the experimental observations with an accuracy of 96% is extended for higher dock magnetic field strengths, and found that an EMHGS utilizing 6000AT dock coil and magnetic field sensors of same sensitivity could have a homing guidance range of 72 m. Based on a priori magnetic map, the system is capable of computing the vehicle range and velocity, serving critical inputs for realizing effective AUV short range homing and docking.

1. Introduction

Autonomous Underwater Vehicles (AUV) have a wide range of applications in the scientific, military, commercial, deep sea search and policy sectors [1,2]. The global AUV fleet is likely to reach 825 units in 2018, a 42% increase compared to 2014 [3]. Their ability to operate autonomously makes them well-suited for exploration activities in the challenging environments, from the world's deepest hydrothermal vents to locations beneath the polar ice sheets [4,5,6]. The key challenge to the AUV operations is the finite mission duration due to the limitation in the on-board energy and data storage. In case of deep water AUVs, a significant portion of the energy is expended during the ascending and descending phases. In the AUVs used for coastal surveillance and oceanographic applications, the effective operation time is limited by the battery capacity [7]. In order to overcome these limitations and to increase the subsea mission duration, underwater homing and docking stations connected to the mother ship or shore facility, with provisions to recharge the batteries, upload the acquired mission data and download the mission profile are proposed [8,27,28,29]. The paper describes the various stages and systems involved in the underwater homing; concept and testing of a bio-inspired electromagnetic homing guidance system (EMHGS) using an experimental setup, and validation of the results using an electromagnetic finite element analysis (FEA) software. The validated FEA model is used to determine the effectiveness of the EMHGS in offering homing support over an increased spatial domain. The capability of the system in determining the range and vehicle velocity parameters based on a priori onboard magnetic map, and its use in realizing precise field-scale AUV short range EMHGS are also discussed.

1.1. Underwater homing stages

The underwater homing guidance system has to provide a reliable guidance for the AUV to return to, and maneuver into the dock, taking into consideration the AUV dynamic response capabilities and the residual energy in the AUV batteries. Fig. 1 shows the various stages involved in the underwater homing guidance.

For an approaching AUV, long-range homing guidance, usually in the range of few kilometers is done using the proven acoustic base line systems with acoustic transmitter and receivers located in the docking station and in the AUV respectively [9]. The AUV com-

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Nomenclature

AUV	Autonomous underwater vehicle
EMHGS	Electromagnetic homing guidance system
DOF	Degree of freedom
AT	Ampere turns
FEA	Finite element analysis
PLC	Programmable logic controller
CPU	Central processing unit
UART	Universal asynchronous receiver transmitter
SRAM	Static random access memory
DVL	Doppler velocity log

putes its range and bearing with respect to the dock for the required course correction. When the AUV approaches closer to the dock, vehicle orientation/pose correction becomes increasingly important to ensure reliable docking, and this requires precise AUV spatial measurements with high update rates with adequate temporal resolution. Determining the orientation of the AUV using acoustic systems with high update rates involve extensive signal conditioning and it is challenging with the limited residual on board energy. Moreover, acoustic systems will have increased complexity if it must operate near the surface, bottom, or near acoustically reflective boundaries [10]. The profile of the docking station also decides the precision requirements of the homing guidance system. A conical dock imposes lesser constraints on the docking section and increased constraints on the homing system, while it is vice-versa for an omnidirectional dock. When the AUV is closer to the docking station, in the order of few meters, short range homing guidance could be offered using optical and electromagnetics-based methods [10,11]. Optical based guidance techniques are quite challenging in the turbid and bio-fouling prone environments, and effective only within the line-of-sight [12]. The electromagnetics-based homing guidance techniques are immune to water turbidity, bubbles, floating organic matter, biofouling and reflective boundaries.

1.2. Bio-inspired concept of EMHGS

Migrating birds use magnetic, olfactory, visual and inertial clues to trace back their way home, when displaced several kilometers [13]. There is a growing evidence for the involvement of the geomagnetic field in the map/geo position sense of vertebrates and homing pigeons. During the flight, they have the capability to detect magnetic anomalies and compile the information in the mental map for use as magnetic signposts in the future [14]. It is reported that spinning lobsters possess magnetic material that provides magneto-receptive function and known to have magnetic compass sense. Natural and manipulated changes of the magnetic field have shown to affect the homing behavior of birds to a varying degree. Artificial fields applied to the pigeon's head on the release site disrupt the ability of the bird to maintain a constant compass course. Even changes in the magnetic field strength in the order of few percentage are found to significantly affect the orientation capability of homing pigeons [15,16]. Studies reveal that ocean waves and the geo magnetic field together serve as orientation clues for newly hatched turtles as they migrate to sea for the first time [17]. Thus the bio-inspired concept of the EMHGS is based on pigeons and sea turtles which use the geomagnetic field for determining their location and directional/compass sense to orient them in the appropriate homeward direction from the displaced locations. Fig. 2 illustrates the concept (patent pending) of the EMHGS.

An alternating dipole magnetic field of fixed frequency and power is generated using the electric coils located in the dock. The unique frequency is used to enable the AUV detect the produced magnetic signature demarcated from the static earth magnetic field, other regional magnetic signatures and stray fields. A differential magnetometer system is located in the approaching AUV, with magnetic field intensity sensors [30] located in the forward and aft ends. The AUV confirms its heading towards the docking station when the forward located sensor measures a relatively higher magnetic field strength compared to the aft located sensor. With a priori spatial magnetic field intensity map on-board the AUV memory (for the specific dock coil power), the forward end sensor measurement provides the distance (range) of the AUV from the docking station. The difference between the magnetic field strengths measured by the forward and aft sensors provides the field gradient, in turn the bearing angle. The bearing angle is the angle between the axis of the dock and the AUV, which provides the orientation of the approaching AUV with respect to the dock. Ideally, bearing angle has to be corrected to zero for achieve a successful dock and for ensuring proper mechanical alignments required for underwater wireless power charging and optical data transfer systems [18]. The minimum bearing angle is achieved when the magnetic field gradient is the maximum. The figure shows the magnetic field sensors reading

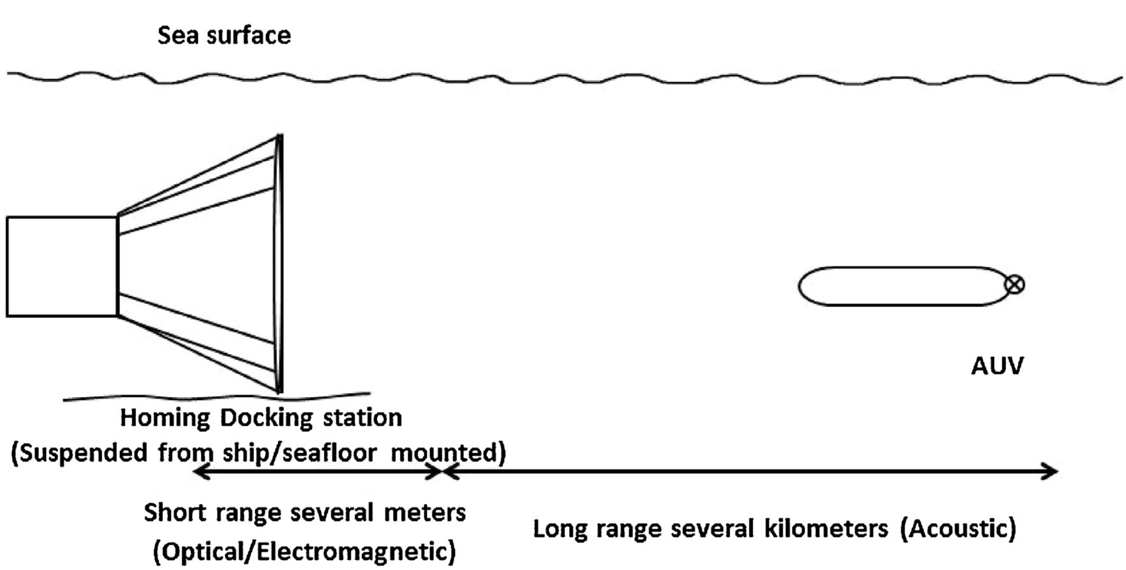

Fig. 1. Stages involved in AUV homing.