Proceedings of the 8th IFAC International Conference on Manoeuvring and Control of Marine Craft
September 16-18, 2009, Guarujá (SP), Brazil

Design of a Lateral-Line Sensor for an Autonomous Underwater Vehicle

Nora Martiny, Stefan Sosnowski, Kolja Kühnlenz, Sandra Hirche *
Yimin Nie, Jan-Moritz P. Franosch, J. Leo van Hemmen **

* *Institute of Automatic Control Engineering, Munich, 80290 Germany (e-mail: sosnowski@tum.de).*
** *Physik Department T35, Technische Universität München, 85747 Garching bei München, Germany (e-mail: jfranosc@ph.tum.de).*

Abstract: In an ongoing research project an autonomous underwater vehicle is to be built that will detect, localize, and avoid objects by means of a fully passive sensory system. Using hot-wire anemometry it measures local water velocities at the vehicle's hull and thus mimics the lateral-line system of fish and many amphibians. Fish often use the lateral-line system as their only means for navigation, especially under poor visual conditions. Simulations and theoretical calculations of the flow around an underwater vehicle show that velocity measurements with hot-wire anemometers enable an underwater vehicle to detect surfaces, so that no clear sight or active scanning is necessary for collision avoidance. A first series of experiments validates theoretical calculations and shows that a vehicle can detect parallel movement to a wall.

Keywords: artificial lateral line, autonomous underwater vehicle (AUV), object avoidance, Mexican cave fish *Anoptichthys jordani*, underwater sensors

1. INTRODUCTION

Just after hatching the blind Mexican cave fish (*Anoptichthys jordani*) has well-developed eyes, but does not react to visual stimuli. The eyes degenerate later. Nevertheless, the fish is able to avoid (navigate around) objects in its aquatic environment. It appears to "perceive" the objects as it passes by (Teyke, 1985; Abdel-Latif et al., 1990).

In the ongoing research project the authors analyze hydrodynamic stimuli as they arrive at *Anoptichthys jordani's* lateral-line system during object avoidance. Hydrodynamic stimuli have been calculated approximately. For a technical demonstration an underwater vehicle is built. The vehicle will use a sensory system based on the lateral-line system of fish and many other aquatic animals. The sensory system shall detect surfaces under water and also, if possible, smaller objects, by measuring the changes in local water velocity caused by these objects. The underwater vehicle shall then change direction accordingly so as to avoid collisions.

Fields of possible applications for such a vehicle could be turbid water with very poor vision as in canalization, pits filled up with water, and swamped buildings. Even under good visual conditions the lateral-line system is useful to avoid collisions and to relieve some burden from the camera system. Future applications of an underwater vehicle equipped with a lateral-line system could therefore be surveying and mapping of waters where humans cannot dive, e.g., because of poor vision, narrow space, or danger of collapse.

2. RELATED WORK

The lateral-line organ of fish and its functionality has been (and still is) investigated in a variety of fields, ranging from biology to neurology, biophysics and engineering. Previous work has covered the neurological aspects of information processing in lateral-line systems (Bleckmann, 1994; Coombs et al., 2000; Franosch et al., 2005; Goulet et al., 2007; Curcic-Blake and van Netten, 2006). At the University of Illinois at Urbana-Champaign scientists (Fan et al., 2002) are trying to build an artificial lateral-line sensor by replicating the hair cells using MEMS technology. A water flow parallel to the sensor bends the cilium in flow direction and a strain sensor surveys the deflection which in turn depends on water velocity. Another fish-like system, which is related in its functionality to the lateral-line organ, has been subject to research at the California Institute of Technology, Pasadena (MacIver et al., 2004). Finally, during evolution, the weakly electric black ghost knifefish (*Apteronotus albifrons*) has developed a system to sense its surroundings by a weak (approximately 1 mV/cm) self-generated electric field causing voltage perturbations due to the difference in electrical conductivity between an object and water.

3. AUV CONCEPT

The development of an autonomous underwater vehicle (AUV) is an educational student project. Therefore, and due to the desire for a small-scale, highly maneuverable, modular AUV, most of the components are self-developed and self-built. Each subsystem is a separate module that communicates over CAN bus. In a later stage of the project the vehicle will consist of stackable modules containing

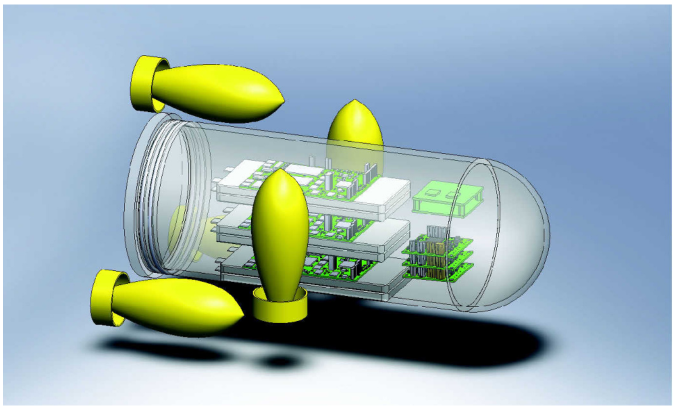

Fig. 1. AUV CAD: Conceptual 3D drawing of the vehicle.

the subsystems. Up to now an acrylic tube with diameter 14 cm and length 24 cm will house all modules. The AUV is composed of the following subsystems.

Propulsion The propulsion system consists of five encapsulated thrusters driven by brushed DC-motors. Each thruster can generate thrust up to 7 N. They are controlled by three motor-controller units that receive their commands via a CAN bus. Three of the motors are planned to face in the forward direction of the AUV, placed around the tube on the corners of an equilateral triangle. In this configuration forward and backward motion can be controlled, as well as pitch and yaw angles. The remaining two motors are placed perpendicular to the triangle configuration, controlling up- and downward movement and the roll angle. The placement of the motors enables control over 5 out of 6 possible degrees of freedom, making the robot highly maneuverable, whilst being able to compensate external disturbances directly (besides lateral disturbances).

Energy management The robot is powered by 12×3.7 V lithium polymer accumulators with 10 Ah each, resulting in a total of 20 Ah at 22.2 V nominal voltage. Lithium polymer accumulators were chosen for their high energy density and their capability of producing a high current. Due to the risks involved with lithium polymer technology and for providing status information, the authors have developed an energy management system that takes care of monitoring the cells and ensuring safety during charging or discharging. Voltage and current status are available via a CAN bus and LCD display.

Pressure sensor array To determine the absolute diving depth a pressure sensor array is used, with four sensors distributed on the robot.

Processing unit and inertia measurement unit The main processing unit is a 60 MHz ARM7 processor coupled with an inertia measurement unit from Ascending Technologies. In the inertia measurement unit sensor data from three MEMS gyroscopes, a three-axis acceleration sensor, a three-axis magnetometer and the pressure data is fused and passed on in preprocessed form to the command unit for stable and reliable angular and translational data. For position tracking at the surface a GPS module is included, as well as a wireless Zigbee transceiver for communication with the operator.

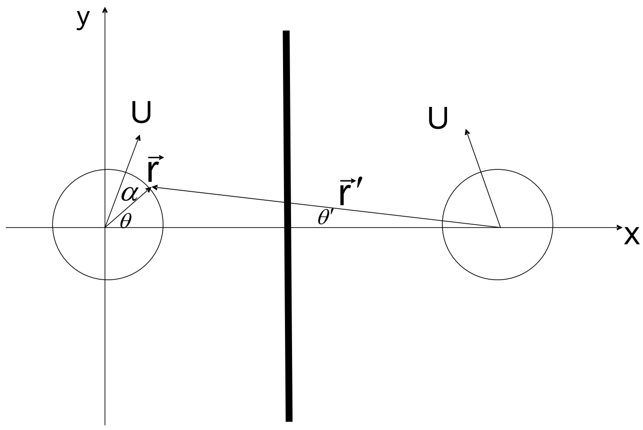

Fig. 2. A mirrored sphere to satisfy the boundary condition at the wall.

Lateral-line sensor system The proposed lateral-line sensor system, installed on the frontal hemisphere, will detect objects in such a way that the vehicle can avoid collisions. The installation on the front part provides laminar flow and maximum distance to the turbulence inducing thrusters. It is planned to install an array of up to 40 sensors.

4. THEORETICAL CALCULATION OF THE FLOW AROUND THE VEHICLE

We approximate the underwater vehicle by a sphere with radius a whose center has a distance D from a wall. The boundary condition that water flows only parallel to the wall is satisfied by introducing a "mirror" sphere that moves in the mirrored direction at the opposite side of the wall, see Fig. 2.

This approach is an approximation insofar as the boundary condition at the surface of the first sphere is disturbed by the presence of the second sphere and thus boundary conditions are only satisfied approximately. The approximation is exact for the limit case $a \to 0$ or $D \to \infty$.

A moving sphere with radius a and velocity $\boldsymbol{U}$ that currently passes the origin of the coordinate system in an incompressible ideal fluid causes a velocity field $\boldsymbol{v}(\boldsymbol{r})$ that can be described by a velocity potential (Lamb, 1932)

$$\varphi_0(\boldsymbol{r}) = \frac{a^3}{2|\boldsymbol{r}|^3}\boldsymbol{U} \cdot \boldsymbol{r}$$

such that

$$\boldsymbol{v}(\boldsymbol{r}) = -\operatorname{grad} \varphi_0(\boldsymbol{r}) .$$

Say the left sphere in Fig. 2 is causing a velocity potential φ_0 and the "mirror" sphere is causing a velocity potential φ'. Then the total velocity potential is

$$\varphi = \varphi_0 + \varphi' = \frac{a^3}{2r^3}\boldsymbol{U} \cdot \boldsymbol{r} + \frac{a^3}{2r'^3}\boldsymbol{U'} \cdot \boldsymbol{r'} .$$

In case the sphere is moving parallel to the wall the condition $\boldsymbol{U} \cdot \boldsymbol{r} = \boldsymbol{U'} \cdot \boldsymbol{r'}$ holds, therefore

$$\varphi = \frac{a^3(\boldsymbol{U} \cdot \boldsymbol{r})}{2r^3}\left[1 + (\frac{r}{r'})^3\right] .$$

Using a polar coordinate system (r, θ), cf. Fig. 2, one gets

$$\varphi = \frac{a^3 U \sin\theta}{2r^2}\left[1 + \frac{r^3}{(r^2 + 4D^2 - 4Dr\cos\theta)^{3/2}}\right]$$