Design of an Underwater Vehicle for use in Basin Experiments, Development of MARIN's Modular AUV

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Abstract: MARIN is designing and building a modular autonomous underwater vehicle (mAUV). The vehicle will serve as a platform for research projects on autonomous vehicles, to be carried out in our model basins. The modular design will enable future extensions with additional sensors and actuators. The design of the vehicle and its control system is aimed at combining capabilities for position keeping (zero speed) and track sailing (medium and high speed). The vehicle is controlled in all 6 degrees of freedom, without any a priori limitations. This paper discusses the design and construction of the vehicle. The overall design of the vehicle is discussed, as well as the selected actuators and all internal mechanical, electrical and instrumentation systems.

Keywords: Autonomous vehicles, numerical simulations, propulsion control, vehicle dynamics, inertial navigation, navigation systems, command and control system

1. INTRODUCTION

The technology enabling the design and application of autonomous vehicles is developing rapidly. Sensors and other electronic components have become relatively cheap and the software to control the vehicles is becoming more and more advanced. Areas of (future) application include self-driving cars, unmanned surface ships, small unmanned aerial vehicles and autonomous underwater vehicles. Developments may further accelerate as knowledge and experience are exchanged between the different areas of application.

The Maritime Research Institute Netherlands (MARIN) is developing tools and methods to investigate the performance of autonomous vessels, at the surface (USVs), as well as under water (AUVs). The applied research methods include time-domain simulations, scale model tests, CFD and interactive training simulators. As part of this research, MARIN is currently designing and building a modular autonomous underwater vehicle (mAUV) for use in model basin experiments. The modular design enables future extensions with additional sensors and actuators. Existing underwater vehicles are usually capable of either accurate positioning at zero speed (ROVs) or efficiently travelling at higher speeds (AUVs). The design of the mAUV and its control system is aimed at combining both capabilities.

The mAUV is designed and built using MARIN's existing expertise in submarine hydrodynamics (Carrica et al. (2016), Overpelt et al. (2015)), dynamic positioning (Cozijn et al. (2015), Arditti et al.(2018)) and thrusters (Dang (2014)) as a starting point. Research projects on the performance of AUVs will allow us to combine the existing hydrodynamic and vehicle control knowledge and further extend into the domain of autonomous vehicles.

2. DESIGN REQUIREMENTS

The first step in the design of the mAUV was the definition of a number of design requirements. Our aim was to develop a flexible platform for our research activities and to construct a vehicle capable of position keeping at zero speed and following tracks at medium or high speed. In summary, this lead to the following design requirements :

- The vehicle should be controlled in all 6 degrees of freedom, also at zero speed, without any a priori limitations related to large angle vehicle orientations.
- The vehicle design should be able to efficiently travel at medium to high speed with sufficient battery capacity to carry out uninterrupted experiments for several hours. To reduce drag loads attachments outside the streamlined hull shape should be avoided as much as possible.
- The vehicle should have a modular construction, to allow different configurations, as well as future additional sensors and actuators.
- The control software should be modular and easily configurable, so that the vessel autonomy can be developed and improved step-by-step.

The above requirements have guided the concept design of the vessel and the selection of its hull geometry and actuators. This is further discussed in the following section.

3. VEHICLE DESIGN

The first steps in the design of the mAUV were the selection of the general concept, the actuators and the dimensions of the vehicle. Subsequently, the various components were further detailed until the dimensions were fixed and the design could be finalized.

3.1 Main Particulars

The need to achieve medium to high speeds naturally led to the selection of a slender and streamlined body shape. And since the vessel design should be modular a cylindrical mid section was chosen. Based on the equipment necessary to perform autonomously under water a number of individual segments were defined, as shown in the figure below.

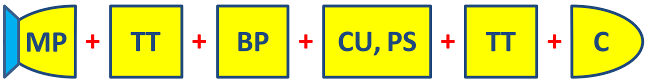

Fig. 1. Modular design of the mAUV, showing segments for main propulsion (MP), tunnel thrusters (TT), battery pack (BP), control unit (CU), position sensor (PS) and camera (C).

The final dimensions of these segments were later defined, considering the hydrodynamic properties of the hull, as well as the internal space required for the equipment inside.

3.2 Hull Geometry

The definition of the mAUV hull geometry was based on the approach used for the definition of the generic submarine hull BB2 by Joubert (2004, 2006). The submarine BB2 is used extensively in many research projects, see for example Carrica et al. (2016) and Overpelt et al. (2015). The aim was to define a body shape with a low resistance, which at the same time could house all necessary equipment for the autonomous operation of the vehicle.

The bow section has an elliptical shape, which can be defined based on its size ratio *a/b*. The elliptical shape will have a smooth transition to the mid section, independent of the selected size ratio. According to Jackson (1992) $a/b = 2.4$ is the optimum from a resistance point of view. For the mAUV a value $a/b = 2.0$ was chosen, to limit the total body length.

The stern section has a parabolic shape, which also by definition has a smooth transition from the mid section. The stern section can be defined by the ration *a/b*, or by the stern exit angle α_{stern}. According to Jackson (1992) the optimum is a stern length ratio $a/b = 3.6$, from a point of view of resistance and propulsive efficiency. This corresponds with an exit angle α_{stern} of 15.5 deg. To avoid adverse inflow conditions at the main propeller, the stern exit angle should not be too large. For the mAUV an angle of 28.3 deg (or $a/b = 1.86$) was chosen, again to limit the total body length. The larger exit angle was considered acceptable, since the mAUV will not have a single main propeller, but 4 ducted propellers. The thruster configuration is further discussed in Section 3.3.

The overall vessel dimensions of the vehicle can also be described by its *L/D* ratio. According to Jackson (1992) for streamlined bodies (drop shape) a ratio $L/D \approx 7$ is the optimum from a resistance point of view. For the mAUV, however, the diameter *D* and length *L* were mostly determined by the internal space requirements. Finally a value of $L/D = 8.9$ was achieved.

The final dimensions of the mAUV are summarised in the table below.

Table 1. Main dimensions of the mAUV

Property	Unit	Value
Length *L*	m	3.10
Diameter *D*	m	0.35
Ratio *L/D*	-	8.9
Displacement Δ	kg	~ 235
Bow section ratio *a/b*	-	2.00
Stern exit angle α_{stern}	deg	28.3
Stern section ratio *a/b*	-	1.86

The resulting hull form is also shown in the two figures below. The bow and stern sections can be clearly distinguished, as well as the parallel mid section.

Fig. 2. Hull geometry of the mAUV (view from the bow)

Fig. 3. Hull geometry of the mAUV (view from the stern)

The images also show the space for the tunnel thrusters and the mounting positions of the stern main propulsion. Both are discussed in more detail in the following sections.

3.3 Thruster Configuration

The thruster configuration of the mAUV was determined such that the requirements of a medium to high forward speed and 6 degrees of freedom vehicle control at zero speed were effectively combined. This resulted in a set of 4 stern thrusters for main propulsion, combined with 4 sets of tunnel thrusters for low speed manoeuvring and vehicle control. This is a distinct difference from to other existing "torpedo" shaped AUVs, such as the Bluefin design (by General Dynamics), the A9 and A18 designs (by ECA Group) and the Remus and Munin designs (by Kongsberg Maritime). These vehicles all rely on rudders and active fins for control, which have no effect a zero forward speed.

At the stern of the mAUV 4 thrusters with nozzles were mounted. The objective of these thrusters is to generate a longitudinal force and thus act as main propulsion of the mAUV. To save development time commercially available thrusters from Blue Robotics (www.bluerobotics.com) were used. An example is shown in the figure below. These thrusters were selected based on their maximum thrust and the estimated vehicle resistance at a forward speed of 3 m/s.

Fig. 4. Example of T200 type thrusters from Blue Robotics.

The delivered thrusters are normally controlled using brushless electronic speed drives (ESC). For mAUV the motors were enhanced with hall sensors and controlled using servo drives. This enables RPM measurements and RPM and electric current control modes. The orientation of the propeller axis was chosen exactly between the longitudinal vehicle axis and the local orientation of the hull surface. Based on our experience with surface vessels it is expected that this orientation will result in the best inflow conditions at the position of the stern thrusters.

Two pairs of horizontal and vertical tunnel thrusters were included at the front of the vessel, directly behind the elliptical bow. The same was done at the stern. The purpose of the tunnel thrusters is to be able to control the vessel in all directions (except surge). The tunnel thrusters are placed in pairs, so that they can also generate a roll moment. Furthermore, the placement of the pairs of tunnel thrusters is such that sufficient internal space remains for the moving mass at the centre line of the mAUV (see Section 3.4 below).

3.4 Additional Actuators

In addition to the main thrusters and the tunnel thrusters, two additional types of actuators were included, being two ballast (or trim) tanks and a moving mass.

The two ballast tanks are placed at the bow and stern of the mAUV. The amount of water inside can be controlled by a piston inside the tanks. The ballast tanks are used to submerge or surface the vehicle by changing its weight. Furthermore, in submerged condition they can be used to correct any trim of the vessel. During normal (submerged) operation the amount of water in the tanks is kept constant.

The moving mass is placed on the centre line of the mid section of the mAUV. The mass can be moved on a rail along the centre line, using a belt drive motor. By moving the mass, the longitudinal position of the centre of gravity of the vehicle is changed, thus controlling the tilt of the vehicle, see for example Li et al. (2008). Using the moving mass to dive or emerge may be more energy efficient than using the thrusters to change the vehicle attitude. The possibilities of controlling the vessel with the moving mass as an additional actuator will be further investigated in future research.

3.5 Future Extensions

The modular design of the mAUV offers the possibility to include additional actuators and sensors. For example, active fins are foreseen for vehicle control at higher speeds. Furthermore, passive stabilizing planes may be added at the stern to improve directional stability. If necessary, additional sections can be included in the main body of the vessel. For example, a section with a side scanning sonar or a Doppler Velocity Log (DVL) could be added.

4. MECHANICAL, ELECTRICAL AND INSTRUMENTATION DESIGN

4.1 Overview of Internal Systems

The mAUV hardware developments were started based on experiences from the design, engineering and assembly of autonomous model-scale submarines (Carrica et al. (2016), Overpelt et al. (2015)). The requirement for a modular vessel suited for complete 6 degrees of freedom vehicle control demanded upgrades on various components and the applied architecture.

The main internal components of the mAUV are:

- Modular structure for all hull segments, made from aluminium, with connections and provisions for O-ring seals to guarantee a waterproof setup (up to 200 m depth for the hull structure, but currently limited to 20 m due to limitations of the applied depth sensor).
- A fanless mini Windows PC with all control and allocation functions (modelled in XMF, see Section 5). Additional software components for operational control, sensor interfaces and communications were written in C#/.NET and C++. Safety functions are implemented using a combination of PC and PLC technology.
- An iXblue PHINS C3 Inertial Navigation System (INS) (www.ixblue.com) combined with an Xsens MTi-300 Attitude Heading Reference System (AHRS) (www.xsens.com) to measure vessel attitude and rotational speed and to estimate the vessel position. Both units provide quaternion output for full 6 degrees of freedom vehicle control.
- Trim/ballast tanks (2) and moving mass (1) equipped with position controlled servomotors. A total of 12 thrusters equipped with hall sensors, to be controlled in speed mode or torque mode. The hall sensors are used to achieve commutation for the brushless motors and to measure actual rotational speeds.
- A cylindrical shaped 24V power supply with 1.5kWh capacity based on LiOn batteries and a dedicated Battery Monitoring System (BMS) for safe operation. A central void provides space for the moving mass.

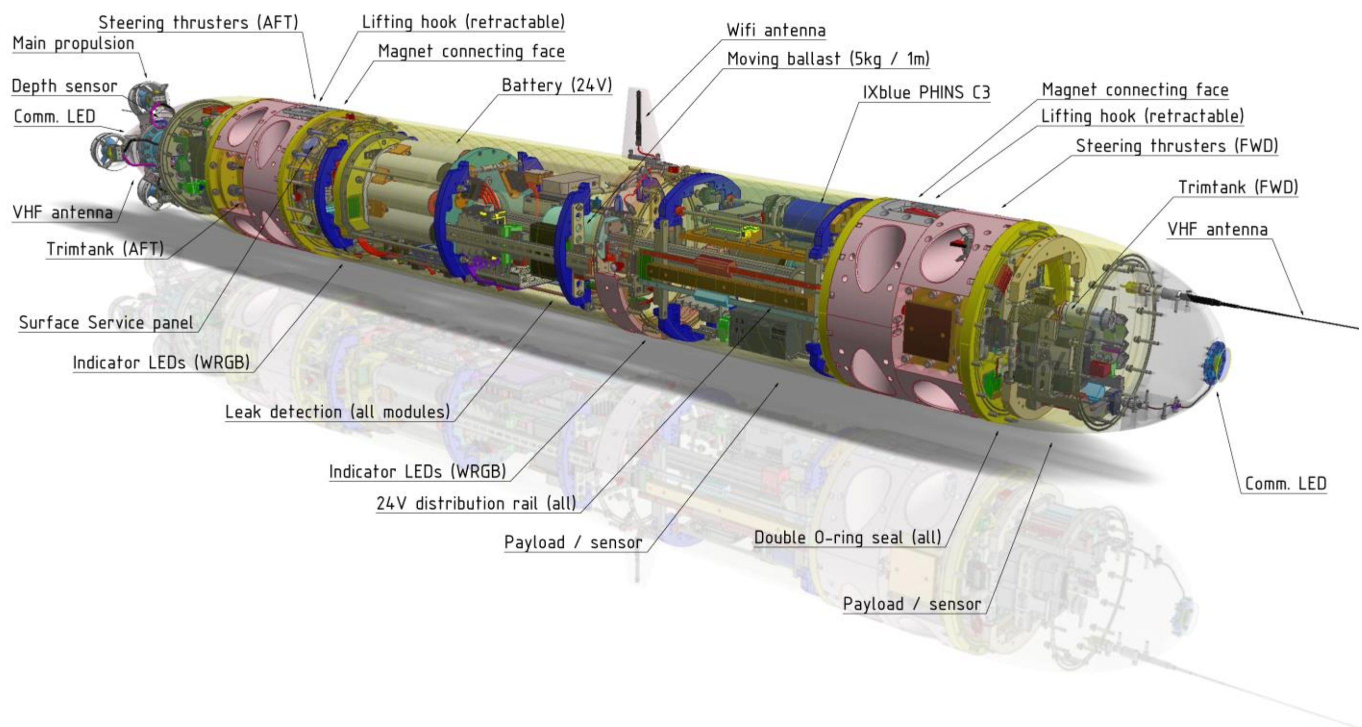

Fig. 5. Overview of the modular Autonomous Underwater Vehicle (mAUV)

- Modems for wireless ethernet communications to supervisory systems located on shore or basin carriage.

A 3D CAD model of the underwater vehicle is shown in Figure 5.

4.2 Position Measurements

To gain more insight in the behaviour of mAUV it is required to measure position, attitude, speed and acceleration, along with information from all actuator controlled elements. Unfortunately, an on board INS cannot measure absolute positions and velocities based on internal sensors alone, unless aiding signals and adequate sensor fusion are provided (similar to GPS aiding). For subsea applications underwater acoustic positioning techniques (e.g. USBL) or Doppler Velocity Logs (DVL) are often used as aiding signals. However, in indoor model test basins the application of underwater acoustic positioning techniques would be hampered by strong reverberations, due to the presence of flat concrete walls and floors. As an alternative, an optical system based on stereo vision and real-time detection and localization of ArUco markers is used to measure the earth-fixed position of the mAUV. This location is also transmitted as an aiding signal to the onboard INS, using a VHF radio connection. The same optical measurement method was also used by Brito dos Santos Cesar et al. (2015), although they used cameras on board the vehicle.

The approach of combined INS and optical measurements also allows efficient execution of free running experiments of the mAUV in the model basin, where a towing carriage will be operating in tracking mode. This mode requires a real-time absolute position measurement of a reference point on the mAUV. The applied set-up is shown in figure 6.

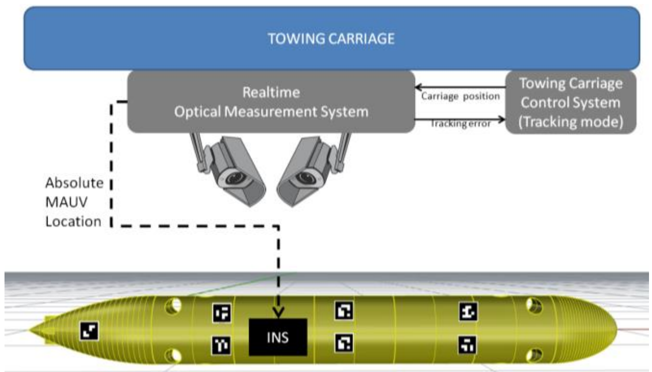

Fig. 6. Optical Position Measurement System

4.3 Thruster Performance

The performance of the selected thrusters in combination with the vessel hull was tested at a number of different forward speeds in MARIN's Deepwater Towing Tank (DT). For these tests a simplified captive test set-up was used with a hull diameter and thrusters locations equal to mAUV, as shown in figure 7. The same set-up was also used to test the underwater visibility of the ArUco markers. The objective of the experiments was to measure the motor currents (design information for the electrical systems) to determine the thrust-RPM relations and to quantify the thrust reduction at higher forward speeds (input for the simulation model).

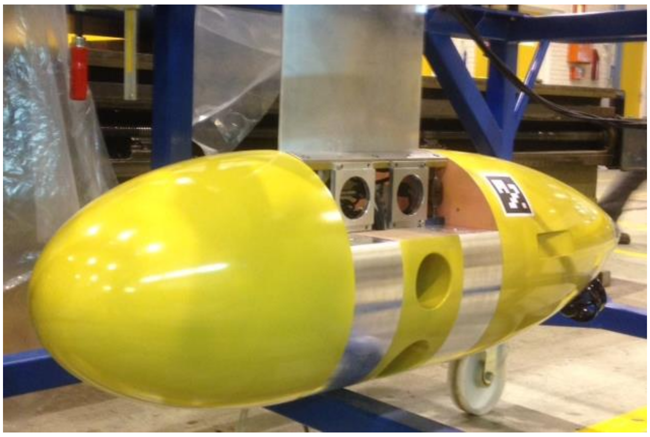

Fig. 7. Captive basin test set-up with ArUco markers

5. TIME-DOMAIN SIMULATION MODEL

5.1 Objectives

During the design of the mAUV we developed a time-domain simulation model of the vehicle, to predict its performance. As the design progressed, the simulation model became more detailed and more accurate, a process which will also continue during construction and testing of the vehicle.

The simulation model of the mAUV can be considered a "digital twin" of the actual vehicle. The simulation model enabled development and testing of the vehicle control system, prior to the construction of the mAUV. This approach is discussed in more detail in de Kruif et al. (2019).

5.2 Software Framework

The time-domain simulation model was made using MARIN's own XMF simulation framework. All time-domain software developments at MARIN, either for engineering purposes (desk top studies, fast time) or for operational training (interactive, real time), are currently made within the XMF framework. The modular structure of the software offers many advantages, including improved quality, reduced maintenance costs and the possibility of re-using and sharing models between different applications and user groups. The XMF based time-domain simulation models are commonly applied for multi-body simulations of floating offshore structures, including mooring, ballast and DP systems, see for example de Vries et al. (2012) and Voogt et al. (2016).

5.3 Description of the Simulation Model

The time-domain simulation model of the mAUV includes the following :

- Rigid body equations of motion, solved in time-domain in 6 degrees of freedom.
- Hydrostatic forces on the hull (buoyancy).
- Hydrodynamic reaction forces on the hull (e.g. drag, lift, …), based on an empirical manoeuvring model.
- Wave forces on the hull, based on undisturbed wave dynamic pressure (Froude-Krylov); no wave diffraction or radiation, valid for small bodies / long waves. Assumed to be acceptable when fully submerged.
- Ballast tanks, static mass.
- Moving mass inside mAUV body. Static position.
- Thruster models, including rate of change of RPMs.
- Propeller thrust and torque, modelled using 4 quadrant propeller diagrams.
- Force based control, see de Kruif et al. (2019).
- Manual joystick control, instead of automatic control.
- Thruster allocation algorithm, to distribute the total required forces (from controller or joystick) over the available thrusters.

The following improvements of the simulation model are foreseen in the near future :

- Improved thruster models, based on thruster performance measurements in basin experiments.
- Improved manoeuvring model, based on basin model tests and CFD calculations. For the calculations similar methods as for submarines will be used, see for example Carrica et al. (2016).
- Improved calculation of the wave forces, including diffraction effects. Commonly used calculation methods assume stationary conditions (e.g. constant draft, constant speed, …) and may therefore not be applicable.

5.4 Simulation Results

Time-domain simulations were carried out to get a first impression of the performance of the vessel and to test the vehicle control system and thrust allocation algorithm. An example of a simulation visualisation is shown in figure 8.

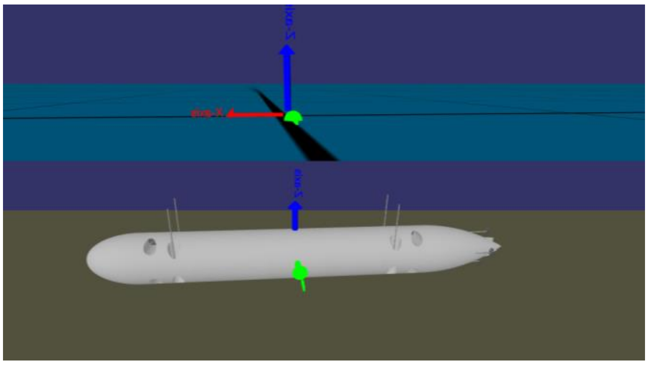

Fig. 8. Time-domain simulation of the mAUV (screen shot)

Manual joystick control using a PC game controller was also tested. The manual joystick control will also be available for the mAUV during testing in the basin. The time-domain simulations, as used for the development and testing of the vehicle control system, are further discussed in de Kruif et al. (2019).

6. FUTURE WORK

The mAUV, as currently designed and constructed, is the first step in a continuous process of extending its capabilities. In the next years the following developments are foreseen :

- Additional actuators will be added. Actively controlled rudders can be used to control the vessel at higher forward speeds, where tunnel thrusters are known to become less effective.
- Additional sensors will be added. These may include a side scanning sonar or a Doppler velocity log. Also sensors for obstacle detection may be added.
- More advanced vehicle control and vessel autonomy will be developed. The additional sensors will be used to better interpret the surroundings, resulting in improved mission execution and obstacle avoidance. The additional actuators will improve performance at higher speeds.
- The simulation model of the mAUV will be further improved to better predict the behaviour of the vehicle. CFD calculations will be performed and analysed to construct an improved empirical manoeuvring model. Furthermore, a comparison with the results of basin experiments will be made.

7. CONCLUSIONS

MARIN has designed and built a modular Autonomous Underwater Vehicle (mAUV) for use in basin experiments. The hull shape of the mAUV was based on design guidelines for submarines. The propulsion system was designed to achieve vehicle control in all 6 degrees of freedom, also at zero speed. This is a distinct difference from to other existing "torpedo" shaped AUVs, which all rely on rudders and active fins for control, which have no effect a zero forward speed.

The mechanical and electronic design of the mAUV was partially based on previous experience in design and construction of submarine scale models for hydrodynamic model tests at MARIN. The mAUV hull construction is modular, making it possible to include additional segments in the future.

The mAUV is a flexible platform for hydrodynamic research in the areas of vehicle control and autonomous underwater operation. Time-domain simulation models of the vehicle and its control system were modelled in the XMF software framework. The simulation model of the mAUV serves as a "digital twin" of the actual vehicle, enabling development and testing of the vehicle control system, prior to construction.

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XMF Time-domain Simulation Model

The design of the mAUV and its control system were supported by a time-domain simulation model of the vehicle, including the main body (mass, buoyancy and manoeuvring forces), all 12 individual thrusters, the 2 internal trim tanks and the internal moving mass. The simulation model was made using MARIN's eXtensible Modelling Framework (XMF) software. The simulation model of the mAUV can be made available for non-commercial use to third parties who are interested in developing control strategies or autonomous capabilities for underwater vehicles.

For more information, please contact the authors.