Design, Modelling, and Simulation of Biomimetic Underwater Vehicle

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KEYWORDS

Biomimetic Unmanned Underwater Vehicle (BUUV); artificial fish modelling; undulating propulsion system; underwater robotics; Matlab Simscape Multibody

ABSTRACT

This paper discusses mathematical model implementations and simulation in various software environments for Unmanned Underwater Vehicles (UUVs), especially biomimetic ones. Gaining accurate simulation models of UUVs is challenging due to many nonlinear phenomena that need to be analysed. Further, the sensors' accuracy and disturbances made by the natural water environment are difficult to predict during the simulation. On the other hand, an accurate simulation model is needed during new algorithm tests provided for increased vehicle autonomy. As a result, mathematical models and their implementation into different software are analysed and discussed in this paper. The model based on nonlinear differential equations is compared to an object-oriented, physical model based on Matlab Simscape Multibody.

INTRODUCTION

Many different constructions of Underwater Vehicles (UVs) are designed in recent years [26], [13], [12]. The variety of designs depends on the specific mission tasks [28]. One types of UV are the biomimetic one. The Biomimetic Unmanned Underwater Vehicles (BUUVs) imitate the behaviour of marine animals [19]. They can operate and records in non-disruptive way fauna and flora [29]. Also, from the energy efficiency point of view, it is desirable to follow the marine animals' way of moving as their behaviour is evaluated throughout millions of years of evolution.

The design of a biomimetic underwater vehicle involves mimicking the physical and behavioral characteristics of marine animals for improved efficiency and maneuverability in underwater environments. The modelling aspect involves creating a mathematical representation of the vehicle's design using computer-aided design (CAD) software, which can then perform simulations to test and analyze the vehicle's performance in different scenarios. The simulation involves running virtual tests of the vehicle's movements, speed, and responses to various conditions and variables, such as water resistance and changes in currents and tides. This helps engineers refine the design, identify potential issues, and make necessary modifications before building a physical prototype.

When designing the BUUV, it is essential to work on vehicle dynamics as well as on the description of the surroundings based on the sensor's parameters [4], [6]. Further, to ensure autonomy, the obstacle avoidance algorithm has to be implemented [8], [7]. As a result of the multidisciplinary model, a wide group of specialists have to work together. The specialist in fluid dynamics has to cooperate with the mechanics who design the construction [15]. The electrical power then needs to be designed with the planned mission time [21]. Also, the propeller characteristics have to be taken into consideration as its' efficiency for the desired thrust, and electric power consumption [16], [11]. Last, but not least, an area of research is vehicle autonomy. Appropriate algorithms should be implemented, including restrictions of a new path calculation time and avoidance collision algorithm implementation, such as a short time of a new path calculation [23], [10], [9] .

Mission Oriented Operating Suit (MOOS) InterVal Programming (IvP) is a set of open source C++ modules for providing autonomy on robotic platforms, in particular, autonomous marine vehicles [1]. The software is suited for marine robotics communication, control, and simulation when the dynamic model of the vehicle is defined [20].

Another example of software that provides libraries and tools to support the process of creating underwater vehicle applications is ROS (Robot Operating System). As presented in paper [30], the platform integrates the 3D marine environment, UUV models, sensor plugins, motion control plugins in a modular manner and reserves programming interfaces for users to test various algorithms.

In general, many multidisciplinary phenomena have to be considered together. A scheme of the phenomena is presented in Fig. 1. Taking into consideration all the above arguments, it is a challenging task to provide a project based on one software.

In the following chapters, the analysis of different software packages and ways of simulation are depicted based on the BUUV example.

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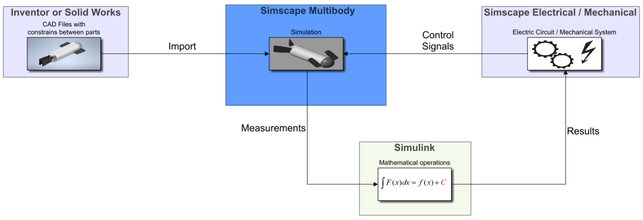

Fig. 1. Scheme of phenomena needed for simulations

MODELLING AND SIMULATION

From a mathematical point of view, BUUV dynamics is described by non-linear differential equations [2]. For BUUV modelling and simulation, six degrees of freedom (DOFs) and six independent space variables are needed. One of the commonly used mathematical models for simulation analysis of underwater marine vehicles was proposed in [2]. The matrix form of the equations is presented in (1).

$$M(\dot{v}) + D(v)v + g(\eta) = \tau \tag{1}$$

where:

M – matrix of inertia (the sum of the matrices of the rigid body and the added masses);

$\dot{v}$ – linear and angular accelerations;

$D(v)$ – hydrodynamic damping matrix;

v – vector of linear and angular velocities;

$g(\eta)$ – vector of restoring forces and moments of forces (gravity and buoyancy);

η - vector of vehicle position coordinates and its angles;

τ – vector of forces and moments of force generated by the propulsion system and environmental disturbances.

Although the equation (1) looks neat, there are more than a hundred parameters needed to estimate for model calculations, and simulations [24]. As presented in [25] an adequate model can be achieved by coefficient estimation using artificial intelligence.

The description of the BUUV mathematical model is discussed in [22], while the propulsion system of the same vehicle is presented in [27], and the depth control for the vehicle is depicted in [14].
In the following sections, the chosen BUUV subsystems are discussed in detail.

Mechanical design

The mechanical project of BUUV, presented in Fig. 2 was prepared in CAD software. The software used enables designers to export some elements to a 3D printer. Also, the centre of gravity and inertia coefficient can be calculated for equation (1), even for curved surfaces. The design can also be used for damping coefficient calculation using Computational Fluid Dynamics (CFD) software [18].

For coefficient validation or parameter measurements, the laboratory test can be adopted, as presented in Fig. 3.

Fig. 2. The design of BUUV

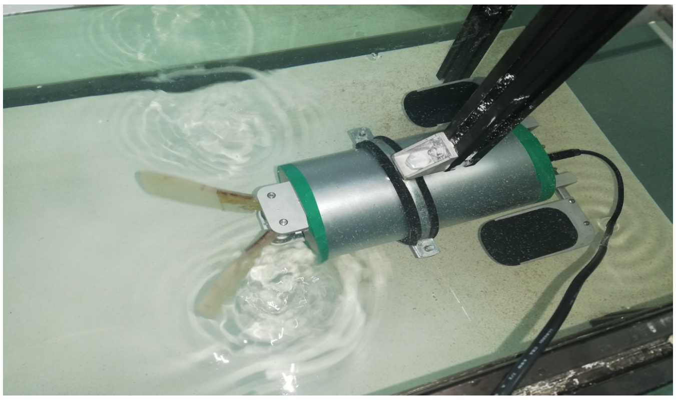

Fig. 3. BUUV tests in the laboratory water tunnel

Hardware design

An example of hardware realisation is presented in Fig. 4, where all internal components can be observed. The biomimetic fins [3] are directly connected to servos. The control algorithms are implemented into the Raspberry Pi module.

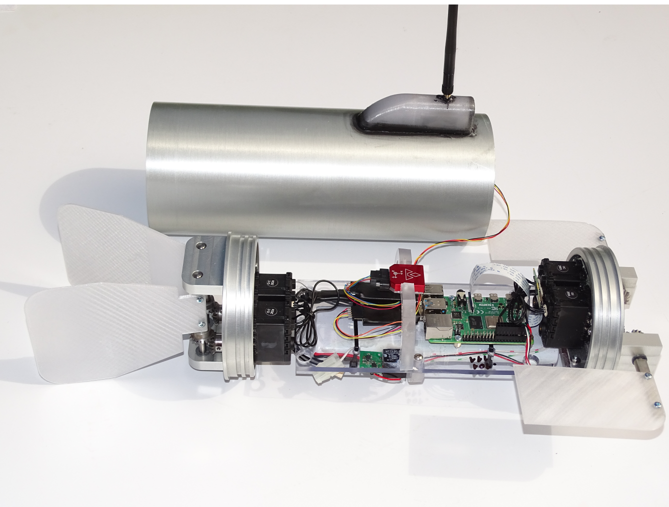

Fig. 4. Hardware project realisation for BUUV

Simulation approach in Simscape Multibody

Simscape Multibody was designed for making simulations of systems based on its 3D CAD files with joints and constraints between elements. It allows to addition of forces and resistances for checking how the model behaves and making the simulation more realistic. The model in Simscape Multibody is made of dedicated blocks. The advantage of this approach is users do not have to create complicated differential equations of 6-DOF space. Build-in solvers (e.g. ODE45) provide a simulation solution and allow users to see the model's behaviour in 3D animation.

The optimisation of motion planning and path-tracking controllers can be provided for models of underwater vehicles [5]. The movement simulation can be provided in 2D and 3D. In the 3D simulation, the coupling effects of the motion of the fluid can be observed including all degrees of freedom. All the parameters (dynamic like turning radius, energy consumption, or sensors parameters) can be monitored, and optimise the path planning can be provided for specific criteria.

A very interesting feature in MATLAB and Simulink is the possibility of deploying designed motion controllers directly on embedded hardware such as microcontrollers and FPGAs.

Description of BUUV's model in Simscape Multibody

The model has been divided into subsystems:

a) mechanical, imported from CAD software;

b) hydrodynamical, as mathematical equations simulating water resistance;

c) electrical, in the form of simulation of main robot's drives;

d) control, in the form of blocks generating control signals for drives.

Modelling of BUUV starts from its 3D model in CAD software, where joints and constraints between elements were defined. Next, the files are imported into Simscape Multibody by the special plug-in. During importing, the block representation of the CAD model (Fig. 2) was created and depicted in Fig. 5.

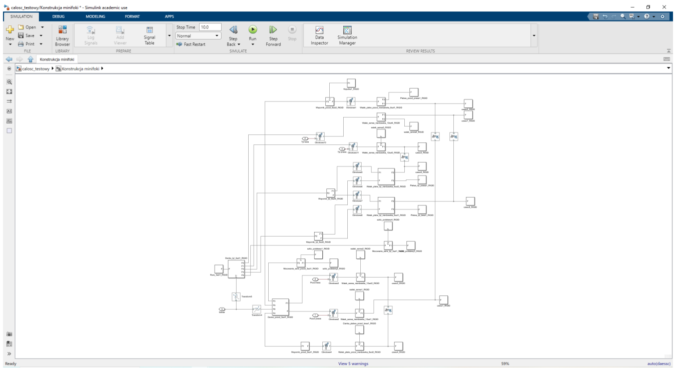

Fig. 5. BUUV's model imported from Inventor to Simscape Multibody

The next step was to provide the main drive in the form of fins driven by servomechanisms. For this purpose, another toolbox was needed - Simscape Electrical. It provides a block's representation of electrical components and their connections in the form of signal lines simulating wires.

Fig. 6 presents the electrical system of the main drive in the form of servomechanism, its power and control system. Parameters of the real used drive as Dynamixel AX-12A were entered into the servomechanism's block. This approach provides getting results of the real component simulation.

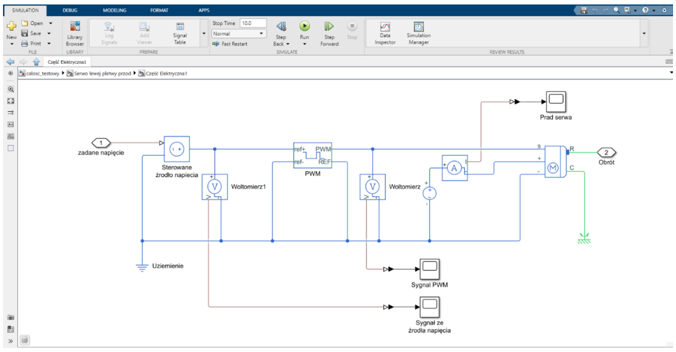

Fig. 6. Electrical subsystem

Additionally, the model was supplemented with elements measuring the circuit's voltage and current to check the control signals' correctness. Sample charts of measurements in the time domain are presented in Fig. 7, where can be observed how the control signal impacts the rotation of the servomechanism.

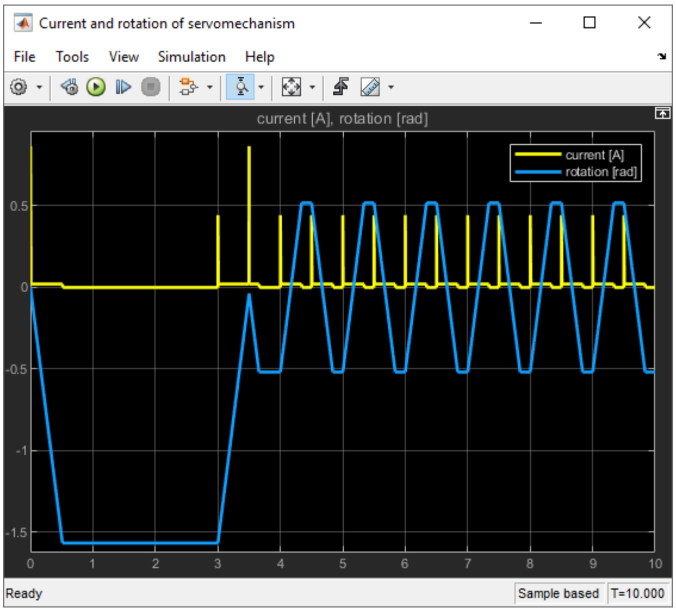

Fig. 7. Sample chart of servomechanism current and rotation during simulation

After modelling drives, the model has to contain control signals to operate servomechanisms as presented in Fig. 8. The repeatable motion of fins was provided by a square analogue signal. It also has a role in configuring servomechanisms and synchronising in the time domain.

The last crucial part of the simulation was to add hydrodynamic forces. Measurements of force generated by fins were described in [17]. Modelling forces affecting the BUUV were visualized in Fig. 9, where the water

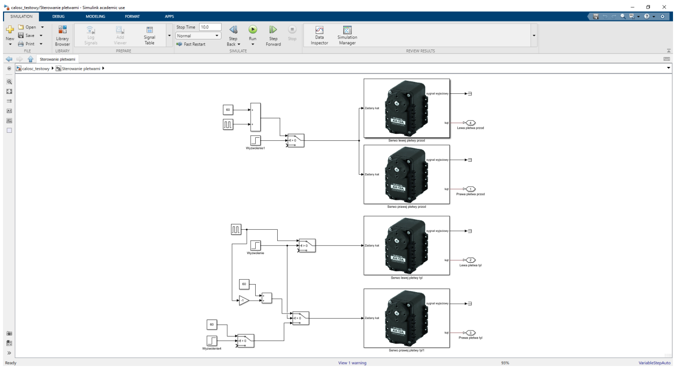

Fig. 8. Main drive of BUUV with control signals

resistances were calculated with using the mathematical formula:

$$R = \frac{1}{2}\rho C S v^2 \tag{2}$$

where:
ρ - water density $[\frac{kg}{m^3}]$;
C - the vehicle shape coefficient [-];
S - cross-sectional area $[m^2]$;
v - the velocity of the vehicle relative to the water.

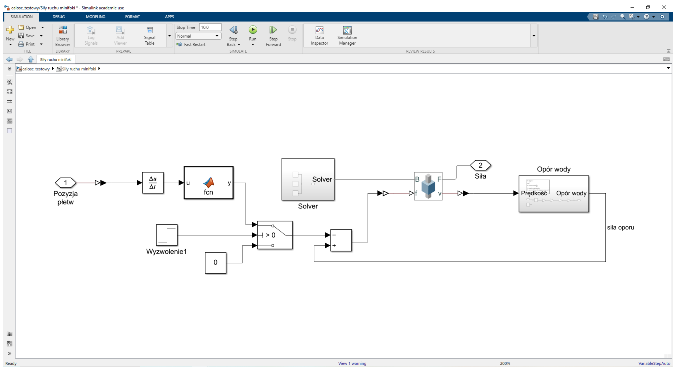

Fig. 9. Modelling forces which affect the BUUV

All discussed above subsystems were connected to one model and depicted in Fig.10.

In this way, designers can detect and correct the defects of a given solution before the model of the designed vehicle is made.

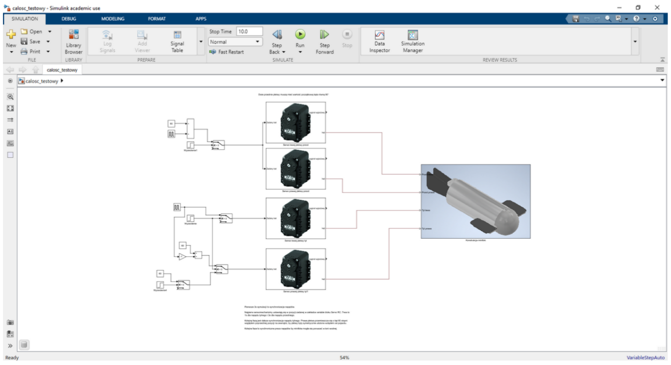

Fig. 10. Block diagram of BUUV's model in Simscape Multibody

CONCLUSIONS

In this paper, mathematical modelling and simulation methods of BUUV are discussed. An appropriate mathematical model requires hundreds of coefficients, many of which are challenging to achieve, especially when the prototype is not built yet. The object-oriented, physical modelling based on Matlab Simscape Multibody is an alternative method to nonlinear differential equations with nonlinear coefficients. The simulation of BUUV was made in Simscape Multibody - one of the toolboxes of Matlab.

In the next stage of the research, the accuracy of the model will be checked, and then the selected control algorithms will be simulated, as well as the vehicle's autonomy functions will be tested.

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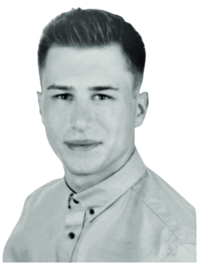

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