Report on the analysis of the state of the art about UUV technologies

Activity 3.1- UUV Technology Downselection
WP3 - Implementation of the Drone-enabled Monitoring System

SUSHI DROP project (ID 10046731)

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ABSTRACT

WP3 focuses on the definition of requirements, procurement, and validation at sea of a drone, i.e. an Unmanned Underwater Vehicle (UUV) for acoustic and optical characterization of the marine ecosystem at different degrees of resolution. The robotic vehicle should be able to acquire autonomously acoustic and optical maps of the benthic environment operating at different resolution and range from the bottom. The system is required to be modular and open for further integration of additional sensors and instruments during the project follow-up.

On the basis of scientific and operational requirements, the characteristics of the Unmanned Underwater Vehicle to be procured as well as of the acoustic and optical sensors for environment perception and ecosystem monitoring are detailed in this deliverable.

UUV CLASSIFICATION, CONFIGURATION, MODEL, SIMULATION AND CONTROL

UUV Classification

Since the seas occupy large part of earth surface a lot of research concerning marine environment, submarine earthquake, sea life, marine resources research, etc, are currently carried out. For these reasons, various underwater vehicles, as Manned Underwater Vehicles (MUV) and Unmanned Underwater Vehicle (UUV) are developed as tools to survey and observe the benthonic and deep sea.

This project is focused on the development of an UUV, whose family is further classified into ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles). It is worth observing that the ROVs are tethered to a surface support vessel by means of a tether cable, which provides a link for transferring power, navigation commands, telemetry and videos between the ROV and the surface. On the other hand, AUVs are untethered and need an internal power supply and a Navigation, Guidance and Control (NGC) system to fulfil the autonomous navigation requirement.

ROV application fields

ROVs are used for different applications, including:

- Aquaculture
- Environmental research for surveying of seas
- Underwater discovery
- Diver Observation, platform and pipeline inspection, subsea installations
- Commercial and salvage diving
- Shipping: inspection of ships.

ROV classification

The ROVs could be classified into:

Observation class ROVs: these small vehicles are equipped with camera/lights and sonar only. They are primarily intended for pure observation, although they may be able to handle one additional sensor, as well as an additional video camera or multibeam sensor.

Working class ROVs: these vehicles are large enough to carry additional sensors and/or manipulators. They commonly have a multiplexing capability that allows additional sensors and tools to operate without being ‘hard-wired’ through the tether cable. These vehicles are generally larger and more powerful than observation vehicles. Wide capability, depth and power variations are possible.

Special use ROVs: tether underwater vehicles designed for specific purposes. Generally, these vehicles are large and heavy than the other ROVs.

AUV application fields

On the other hand, AUVs are becoming more and more popular, since they can operate for long-range missions since they are not limited by the tether cable. Due to technical constraints, AUVs were engaged in limited tasks and missions. Rapid technological development of AUVs is making their use possible in many critical jobs with persistently evolving roles and missions, including:

- Research: among which exploring the sea floor and its lives, tracking and observing shoal of fish, taking water samples.
- Environment Monitoring: to assess environmental status of habitats, fish stocks population and, in general, to monitor the biodiversity of marine ecosystems. Furthermore, long term monitoring of radiation levels, pollution in aquatic habitats, inspection of underwater structures and seabed mapping.
- Search and Rescue: in case of missions and operations in polluted and shallow water.
- Commercial: Most of the oil and gas industry requires seabed mapping and surveying before developing infrastructures.

AUV classification:

A possible classification of AUVs may be based on the size (or weight) of the vehicle, which is further divided in to micro, small, medium or large size. In addition, based on its shape, the vehicle can be designed to have a torpedo shape or to have a non-torpedo shape, depending on the mission requirements. Another possible configuration in which the vehicle can be part of, is related to its depth ability: it is possible to design surface AUVs or vehicles capable to go deeper (up to about 10000 meters). On the other hand, an AUV can be configured based on its spatial and temporal autonomy: the two macro categories to refer to are the range and the endurance, in which we have the sub-categories of ‘short’, ‘medium’ or ‘long’ range or endurance. Moreover, the vehicle can be powered by various power supplies, including batteries, fuel cells and engines. The last category in which the AUV can be part of concerns its possible applications, which have been previously described. Finally, the payload could distinguish the AUV type.

UUV CONFIGURATION

The UUV under developing within the project is a vehicle configurable as both AUV and ROV. The UUV shape of the vehicle will be chosen dependently on the missions to fulfil. In ROV configuration will be installed a tether cable to guarantee the required range. The vehicle is rated for a maximum depth of 300 m and will be able to navigate autonomously in a user-defined area for an estimated mission duration till 6 hours.

UUV Shape

Regarding the design of an AUV, the most used shapes are:

- a torpedo shape, which has less drag with respect to the non-torpedo counterpart, but it needs fins and rudders to control the motion.
- A non- torpedo shape used for low speeds vehicles.
- A bio-inspired shape: nowadays there are some instances where inspiration from biology has been applied specifically to AUVs. Within this approach fin or fish shape AUV/ROV have been proposed and they represent a possible choice for the project AUV/ROV

The “hull”, which houses the electrical systems and the power supply, should be characterized by good accessibility, impact robustness and water pressure withstanding.

ACTUATORS AND SENSORS

The AUV/ROV NGC system is equipped with a Central Processing Unit, responsible for accessing sensors, processing data and setting control outputs. A possible choice of such unit could be within the family of PC/104 boards.

Actuators

For the project AUV/ROV, the propeller propulsion adopted will be based on magnetic coupling (MC) between the propeller and the shaft ([3,4]).

This magnetic coupling is intrinsically a torque limiter allowing to avoid thruster mechanical stress, in other words the shaft and propeller slips in case of an abrupt change of load torque. Moreover, the magnetic coupled thrusters are the most suitable for the autonomous navigation, due to the absence of mechanical losses which in turn produce energy losses. Finally, the magnetic coupling is also highly tolerant of axial, radial and angular misalignment.

Sensors

UUVs are equipped with two classes of sensors: sensor for ecosystem assessment and sensors for vehicle positioning and navigation. Among sensors for ecosystem assessment the following devices can be listed:

- Multi-/single-beam echosounder
- Sidescan sonar (low-grazing angle *swathe* systems)
- Synthetic Aperture Sonar (SAS) in seafloor imaging p.114

- Acoustic Ground Discrimination Systems (AGDS) echosounder
- Sub bottom profiling devices
- Cameras
- Conductivity, Temperature, Depth (CTD) sensors
- Niskin bottles (water samples)
- Acoustic Doppler Current profilers
- Reduction potential sensors (Eh)
- Phase Differencing Bathymetric Sonars

In the usage of these sensors, the speed of survey is important for data quality: fast vessel speeds will result in a lower density of soundings than slow speeds. Thus, speed is a trade-off against data quality and will need to be considered when allocating resources.

Another important factor is related to the characteristics of the ecosystem that have to be monitored (demersal/pelagic fish, scale resolution). Quoting [18]: “Multi-beam and high-quality sidescan along with associated processing software is probably equally expensive, though AGDS is substantially cheaper. Sidescan has the highest resolution, but performs only marginally better than multi-beam for most habitats. AGDS has the lowest resolution, but is good at discriminating bulk sediment properties”.

One of the major challenges for Autonomous underwater vehicles is the positioning and navigation problem [16, 17]. Positioning refers to the determination of the coordinates of the vehicle both in a local and a global reference system; navigation refers to path planning.

Several technical solutions have been developed to solve the positioning problem, all of them are based on the integration of different kinds of internal and external sensors. The most relevant technologies adopted are:

- **GNSS** (Global Navigation Satellite System): this satellite-based technique is used to measure the position of a point everywhere on the globe and in a global coordinate reference system. The vehicle position is normally measured by differential GNSS, while the heading is measured by a Fiber Optic Gyroscope (FOG). GNSS electromagnetic signals are not able to penetrate water; therefore, this technique can be used directly on UUV only when they are on the surface. However, GNSS is essential to correctly locate the mother ship or some buoys, which can serve as reference points for underwater positioning with other instruments. The cost of a differential system is about 15,000 €.
- **IMU (Inertial Measurement Unit) and INS (Inertial Navigation System):** The IMU is a device usually equipped with three-axes rate gyros, accelerometers and magnetometers. In some industrial packages the IMU can be upgraded to full AHRS (Attitude Heading Reference System) or INS capability through a proper software (*https://www.advancednavigation.com/product/motus*). The AHRS provide attitude and heading of the UUV, whilst the INS (Inertial Navigation System), by a proper elaboration of IMU raw data provide, beyond attitude, also the position of the UUV. The IMU is affected by errors due to sensor biases, misalignments and temperature variations which tend to accumulate over time and, therefore, limit the maxim distance autonomously reachable by the UUV. The INS cost for AUV applications is larger than that of aeronautical use and it can go up to 120,000 €. The choice of this device is based on the cost/performance ratio optimization: what we are looking for is an instrument which is quite accurate for the given mission requirements and at the same time without a high cost.
- **ACOUSTIC SENSORS FOR POSITIONING:** acoustic positioning sensors determine the position of the UUV relative to the local reference frame, by employing acoustic transponder beacons. These sensors use an acoustic signal, since they have a lower absorption rate in water compared to the electromagnetic signals used by the GNSS. The most common methods for UUV acoustic positioning system are Long BaseLine (LBL), that uses at least two widely separated beacons placed on the seabed. Clearly, the design and deployment of these sensor arrays is quite

expensive and complicated. An alternative approach is the Short Baseline (SBL), or Ultra-Short Baseline (USBL), that consists in installing three or more beacons on the mother board. USBL provides the relative position of the UUV in respect to the mothership; then, if the mothership is properly positioned with GNSS, also the absolute coordinates of the vehicle can be computed.

- **DOPPLER VELOCITY LOG (DVL):** this acoustic sensor is able to estimate the velocity relative to the sea bottom. The errors affecting the sensor are bias errors, white noise and scale factor errors. It can be noted that the DVL offers an accurate estimate of velocity with zero-mean bias.
- **DEPTH SENSOR:** it provides the depth or vertical position of the vehicle by measuring the pressure of the water column. Different sensors are also developed to measure the sea pressure.
- **Imaging sensors:** they are basically single or stereoscopic cameras that can be used for machine vision and image processing. These techniques can be used for positioning based on target recognition (provided that some known targets are located on the seabed), or for obstacle avoidance and map generation/updating during navigation.

Current research trends for UUVs focus on a data fusion approach starting from the data collected by many different sensors. Most research focussed in particular on the development of stochastic state estimators, such as Kalman filters, efficient recursive algorithms that estimates the state of a linear or nonlinear dynamic system from a series of noisy measurements. More recently, increasing research efforts have been carried out for the development of simultaneous localisation and mapping (SLAM) systems, which exploit sensors information to continuously and simultaneously estimate the position and build incremental maps.

Main Sensor Errors and Data Filtering

The influence of the temperature on inertial navigation systems is due to the device temperature change and the temperature field. In the accelerometer, the change in temperature is due to the environmental temperature change e to the self- heating, which both affect the output of the sensor. Due to this reason, various temperature compensation models are developed to reduce the effect on the sensor outputs.

Finally, a state estimator for processing of the sensor and navigation data is necessary with these kinds of sensors. The most famous one is the Kalman filter algorithm, an efficient recursive filter that estimates the state of a linear or nonlinear dynamic system from a series of noisy measurements.

For the ROV design, the components are almost the same with an additional tether cable and related mechanical devices.

MATHEMATICAL MODEL OF THE UUV

In order to design the Navigation, Guidance and Control system for an UUV, it is necessary to introduce and describe the mathematical model governing the motion of the body. To this aim, two different frames of reference are used: the inertial frame (North-East -Down, NED) and the body frame, which is fixed with the vehicle and rotates with respect the NED with a certain angular velocity.

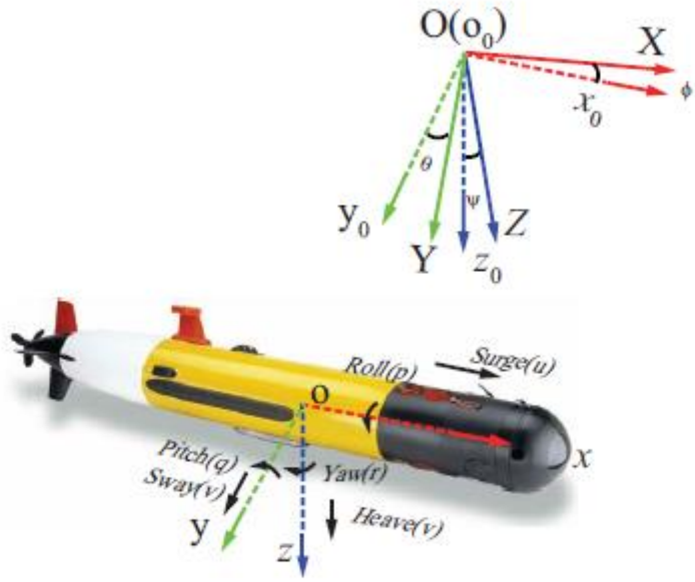


Figure 1. Body and inertial frames of reference (from [14])

The model presented hereafter takes the name of 'Fossen model', from the name of the first person that addressed the study of underwater vehicles model. The UUV is considered as a rigid body, therefore the governing equations are the standard equations describing the translational motion of the centre of gravity CG and the rotational motion about the CG, or more precisely the centre of the body frame. The final model has been implemented as an UUV simulator in Matlab/Simulink, as described below, taking into account that, for the benefit of the project, has to be easily understandable and modifiable.

As shown in figure 2, the 6 DOFs of an UUV are defined as:

surge (longitudinal motion, motion of the UUV in the horizontal plane),

sway (sideways motion, the motion of the UUV in the horizontal plane), *heave* (vertical motion),

yaw (rotation about the z-axis, the vertical one) is the heading of the craft,

roll (rotation about the x- axis, the longitudinal one),

pitch (rotation about the y-axis, the transverse axis).

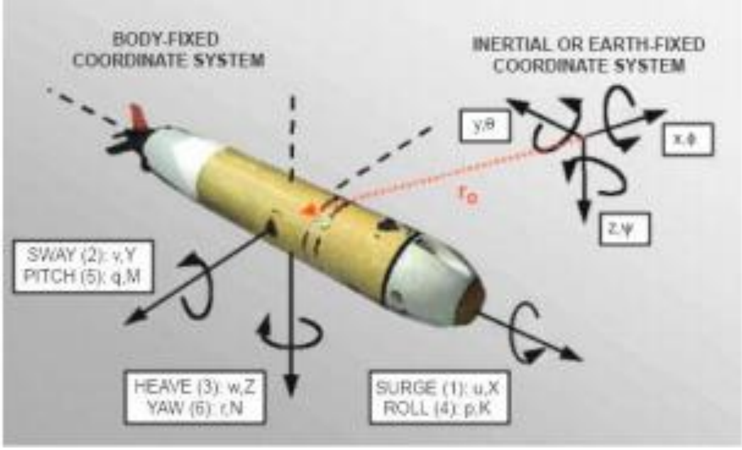


Figure 2. Degrees of freedom (from [15]).

The model of the body is divided into the kinematics part (only geometrical aspects of motion) and into the kinetics part (i.e. the dynamic equation, which regards the analysis of the forces causing the motion of the body).

KINEMATICS EQUATIONS:

The kinematics equations are related to the two following transformations:

- Euler angle transformation: developing of the equation $\dot{p} = R(\Theta)\upsilon$, which projects the linear velocity about the instantaneous axis of the body frame (u, v, w) into linear velocities about the axis of the inertial frame $(\dot{x}, \dot{y}, \dot{z})$ through the roll, pitch and yaw $(\varphi, \vartheta, \psi)$ Euler angles.

- Angular body transformation: $\dot{\Theta} = T\omega$, which is a relation between the angular velocity in body frame (p, q, r) and the time derivative of the Euler angles.

RIGID BODY KINETICS:

The starting point is the equations of the classic rigid body (translation and rotation about CO=origin of the body frame), with the difference that in an UUV the external forces/moments are of the kind hydrodynamics and hydrostatics (added mass effect, gravity, buoyancy and damping effects). The dynamic equation of motion, after all the computations, is written in the following form:

$$M_{rb}\dot{v} + C_{rb}v + M_A\dot{v} + C_Av + D(v)v + g(\eta) = \tau \qquad (1)$$

From this equation, the output is the vector $v = (u, v, w, p, q, r)^T$ describing the linear and angular velocities of the body about the three instantaneous axes.

In equation (1), the first two terms are called ‘rigid body terms’, the hydrodynamic terms are $M_A\dot{v}, C_Av, D(v)v$, whilst $g(\eta)$ is the hydrostatic term (function of the position of the UUV) and finally τ is the control input. In the rigid body terms, the matrix C_{rb} represent the Coriolis vector and the Centripetal vector term, due to the rotation of the body frame with respect to the inertial frame.

The hydrostatic contribution embeds the effects of the *gravity acceleration and of the buoyancy force* and moment, while in the hydrodynamic terms there are *the added mass and damping effects*.

To clarify what the 'added mass' represents, a definition from [1] is reported:

"The hydrodynamic added mass can be seen as a virtual mass added to a system because an accelerating or decelerating body must move some volume of the surrounding fluid as it moves through it. Moreover, the object and fluid cannot occupy the same physical space simultaneously."

The damping term models different contributions of damping, among which (again from [1]):

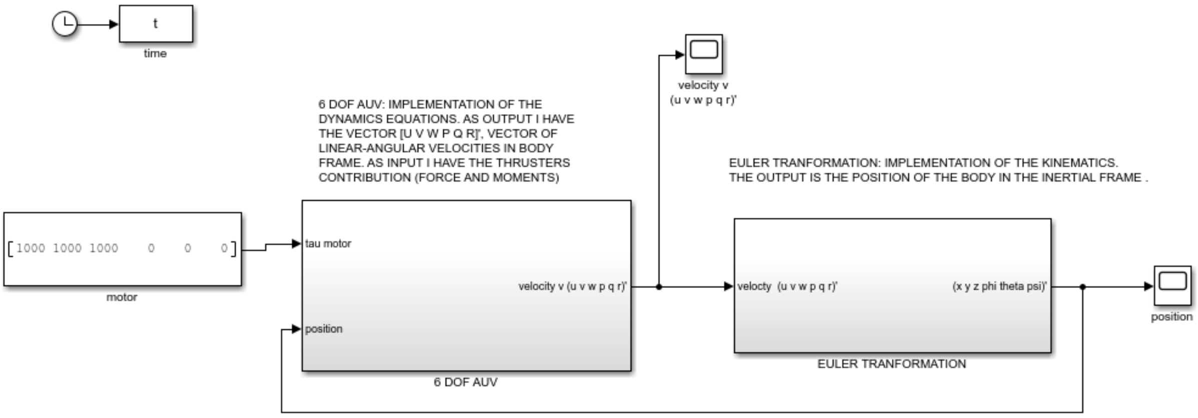
- *Potential damping*;
- *Skin friction* (due to laminar boundary layer theory and due to a high-frequency contribution linked to a turbulent boundary layer. This is usually referred to as a quadratic or nonlinear skin friction);
- *Wave drift damping* (interpreted as added resistance for surface vessels);
- *Damping* due to vortex shedding and lifting forces (they arise due to the linear circulation of water around the hull and due to the cross flow drag, linked to the vortex shedding).
- *Lifting Forces*: Hydrodynamic lift forces arise from two physical mechanisms: the first one is due to the linear circulation of water around the hull, while the second mechanism is a nonlinear effect, commonly called crossflow drag, which acts from a momentum transfer from the body to the fluid. This secondary effect is linked to vortex shedding.

With the purpose of implementing Hardware in the Loop and Software in the Loop tests, investigating the behaviour of the UUV and to design the NGC system, a Simulink simulator has been designed and implemented by UNIBO and CNR of Genova.

The relationship between the simulator and the equations of motion is one-to.one: the simulator 'reflect' the writing of the equations, in order to be easily understood and modified by different people within the project.

Moreover, this simulator has been implemented such as to be adapted for different UUV configurations: only few parameters linked to the geometry need to be changed in the code

Figures 3, 3.1 and 3.2 show the kinematics and dynamic parts implemented on Simulink.



6 DOF AUV: IMPLEMENTATION OF THE DYNAMICS EQUATIONS. AS OUTPUT I HAVE THE VECTOR [U V W P Q R]', VECTOR OF LINEAR-ANGULAR VELOCITIES IN BODY FRAME. AS INPUT I HAVE THE THRUSTERS CONTRIBUTION (FORCE AND MOMENTS)

EULER TRANFORMATION: IMPLEMENTATION OF THE KINEMATICS. THE OUTPUT IS THE POSITION OF THE BODY IN THE INERTIAL FRAME .

Figure 3. Simulink model.

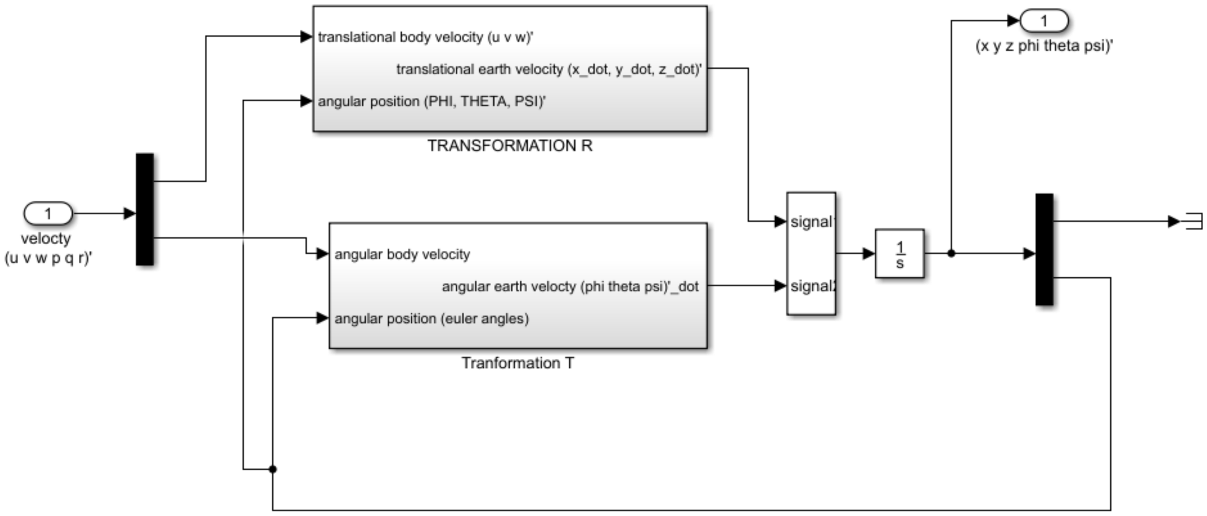


Figure 3.1. Kinematics part on Simulink.

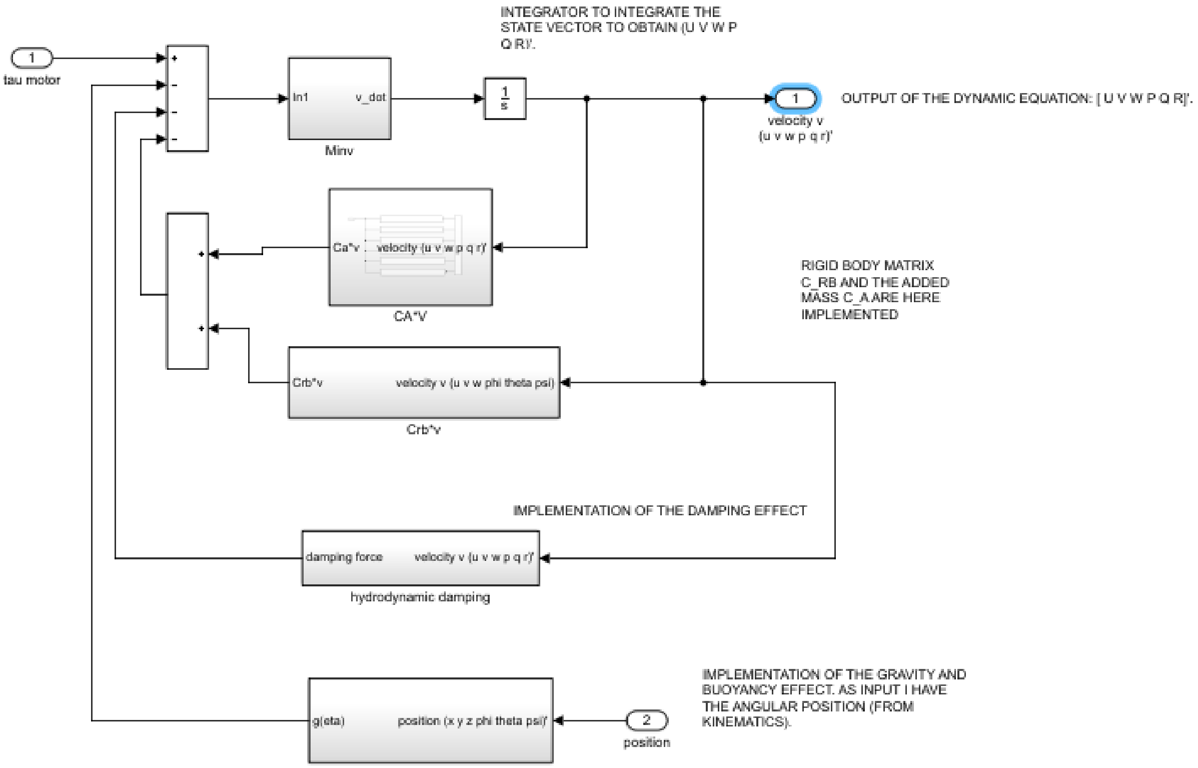


Figure 3.2. Kinetics model on Simulink.

Focusing a little bit on these figures, figure 3 shows how the kinetics and kinematics models interact with each other: the position of the vehicle, which is the output of the kinematics model, is introduced back in the dynamic part to design some external effects.

More precisely, figure 3.1 shows the way how these last two are obtained on the Simulink model. Once the Euler and angular velocity transformations have been designed separately, and once their outputs are integrated in time, the final result we get is the position and attitude of the UUV with respect the inertial frame.

Finally, the way in which the dynamic is implemented is visible in figure 3.2: the various external effects have been designed separately from each other, each of them correspond to a given term in equation (1). The linear and angular velocities in body frame are the output of the dynamics part.

In addition to the equations of motion, the simulator has to be completed with the model of the main sensors, which can be taken from [7], and with the propulsion model.

Testing and debugging of the above described simulator are currently implemented by a comparison with a well-known simulator written in Python Code in Linux operating system [11,12]. Obviously, the Linux simulator is written in a code hardily understandable and modifiable from people different from the programmer.

UUV CONTROL: SURVEY AND INITIAL CHOICE

Finally, a brief description of the most used UUV Control Systems is below proposed. The final choice for the SUSHI-UUV Control System implementation will be a micro controller, such as PC104, able be programmed for a generic Control Law. The implemented control methodology will be the best suited to the required mission, but surely the first choice will be on the classic PIDs that can be used in most of the missions of a UUV.

The control of an AUV is complex due to the non-linear dynamics of the body and presence of complex forces like environmental disturbances. For this reason, depending on the missions required, several control techniques have been developed:

- PID control
- Linear Quadratic control
- Fuzzy Logic Control
- Adaptive Control
- Sliding Mode Control
- Feedback linearization
- H_∞ control

PID: Proportional-Integral-Derivative control is a control loop feedback mechanism, which is used to correct the error between a measured variable and a desired reference variable (or set-point) with a corrective action. The PID controller consists of three different gains: the proportional, integral and derivative gain. The proportional gain determines the reaction to the current error, the integral gain determines the reaction based on the sum of recent errors and the derivative gain determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the output, for instance the power of the thrusters of the AUV.

PID controllers have a good performance, but they do not take into account system nonlinearities that can deteriorate a system's performance or lead to instability.

LINEAR QUADRATIC CONTROL: Optimal control's task is to find a control law for a given system such that a certain optimality criterion is achieved. This is usually a cost function that depends on the state and control variables. A special case of linear quadratic (LQ) optimal control, which can be easily implemented, involves linear systems and quadratic cost functions.

FUZZY LOGIC CONTROL: The fuzzy controller is useful when a mathematical model is not known well or not known at all. The use of fuzzy control on an AUV can avoid the complex hydrodynamic modelling of the vehicle. Furthermore, Fuzzy control allow obtaining good results with systems with high non linearity.

ADAPTIVE CONTROL: Adaptive control is a non-linear control used for uncertain or time varying systems and it is applied on systems with a known dynamic structure with unknown constant or slowly-varying parameters. Adaptive control is useful for AUV's due to their changing dynamics. The controller can adapt itself to varying sea currents or to a different vehicle mass when new equipment is installed. This control is a complex control method and requires the knowledge of the mathematical model.

SLIDING MODE CONTROL: SMC is a switching control law that force the state trajectory of the plant, in the state space, into a sliding surface where it has desired dynamics. The SMC has many advantages, like a fast response, insensitivity to parameter variation and disturbance. Conversely, there are chattering problems.

FEEDBACK LINEARIZATION: In this case the non-linear system is transformed into a linear system by a cascade connect compensator such that the cascade result in a linear system (linearization process). As a consequence, a linear control method can be applied to the linear system. Feedback linearization is applicable in an easy way to underwater vehicles. A disadvantage of this control is that the model of the system needs to be known perfectly, which is difficult in practice.

$\mathbf{H_\infty}$CONTROL: The H_∞ control is a control method for designing a robust controller capable of handling the differences between the physical plant and the model of the plant used for controller design. Designing the weighting matrices requires careful consideration for optimal performance. Common problems involve controller demanded inputs that are higher than what is possible due to saturation.

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