Underwater Robotics

FIELD AND SERVICE ROBOTICS

DIETI
UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II
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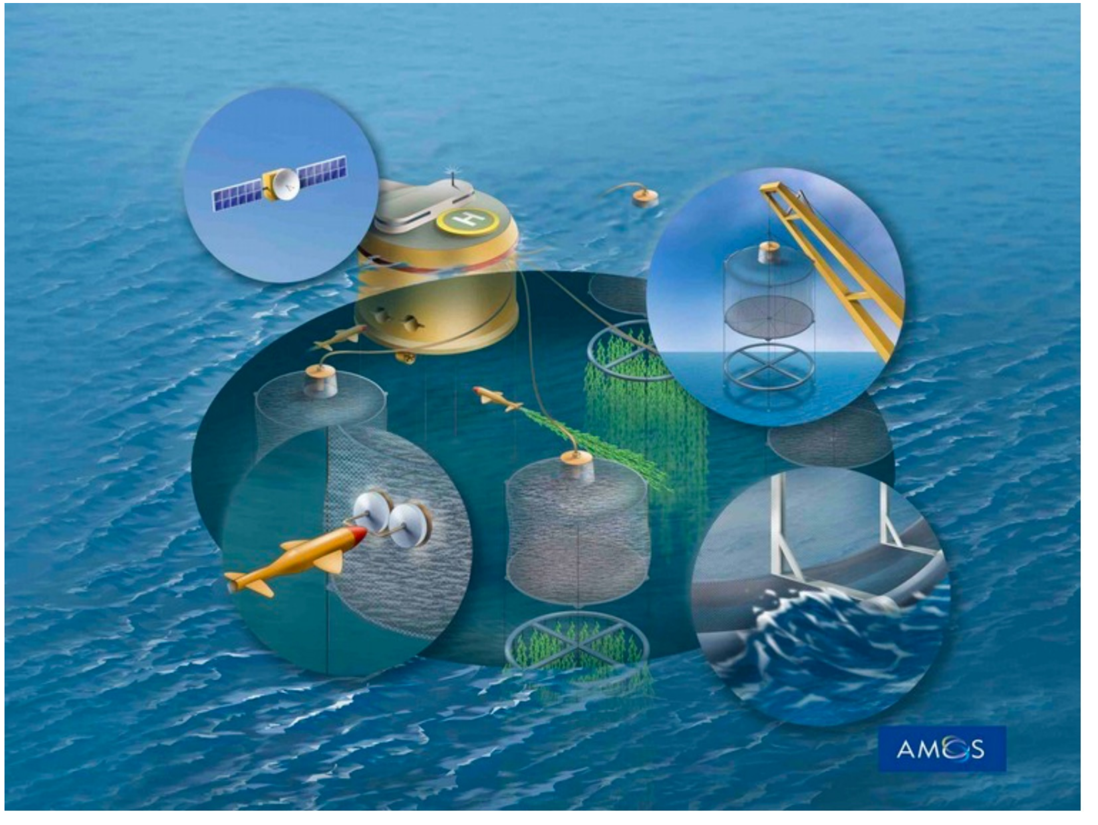
- Almost 2/3 of the earth's surface is covered by water; however, water is precious, it only represents 1/4400 of the total mass of the Earth
- Underwater robots, or unmanned underwater vehicles, can help us better understand marine and other environmental issues, protect the ocean resources of the earth from pollution, and efficiently utilize them for human welfare
- The strong limitation of manned vehicles is the enormous cost (around 8k€ per day) and risk in working in such an hostile environment

- Power/communication cables

https://www.youtube.com/watch?v=9hEDTRU_F2s

- Fisheries and aquaculture

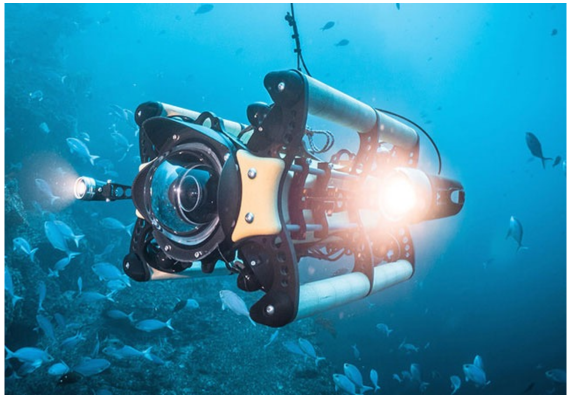


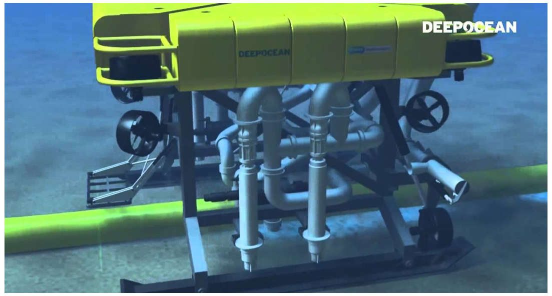
- Decommissioning

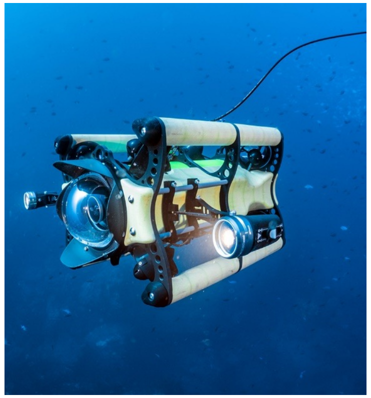
- Other applications
  - Nature science
  - Security
  - Archaeology
  - …

- Oil and gas facilities
  - What is possible:
    - Visual inspection
    - Thickness measurement (UT)
    - Archeology
    - Cleaning
    - Small maintenance
  - What is needed:
    - Power maintenance
    - Increased localization capability

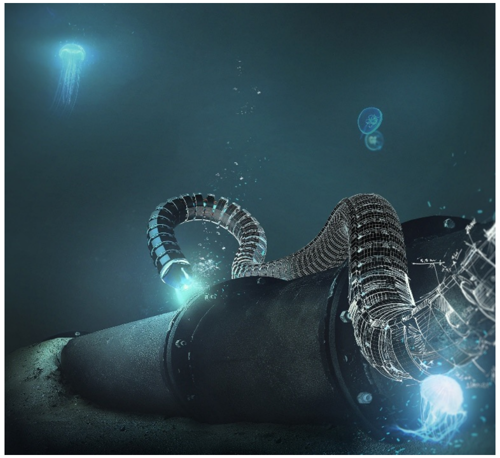
- Underwater inspection and maintenance

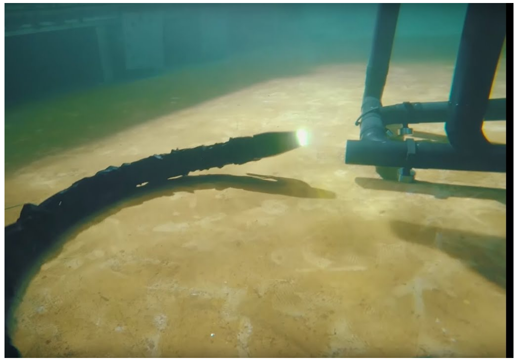


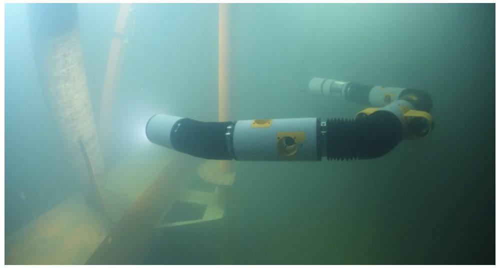


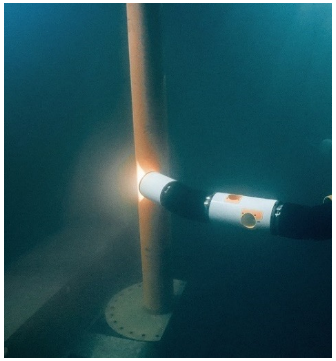


- Underwater inspection and maintenance through snake robots

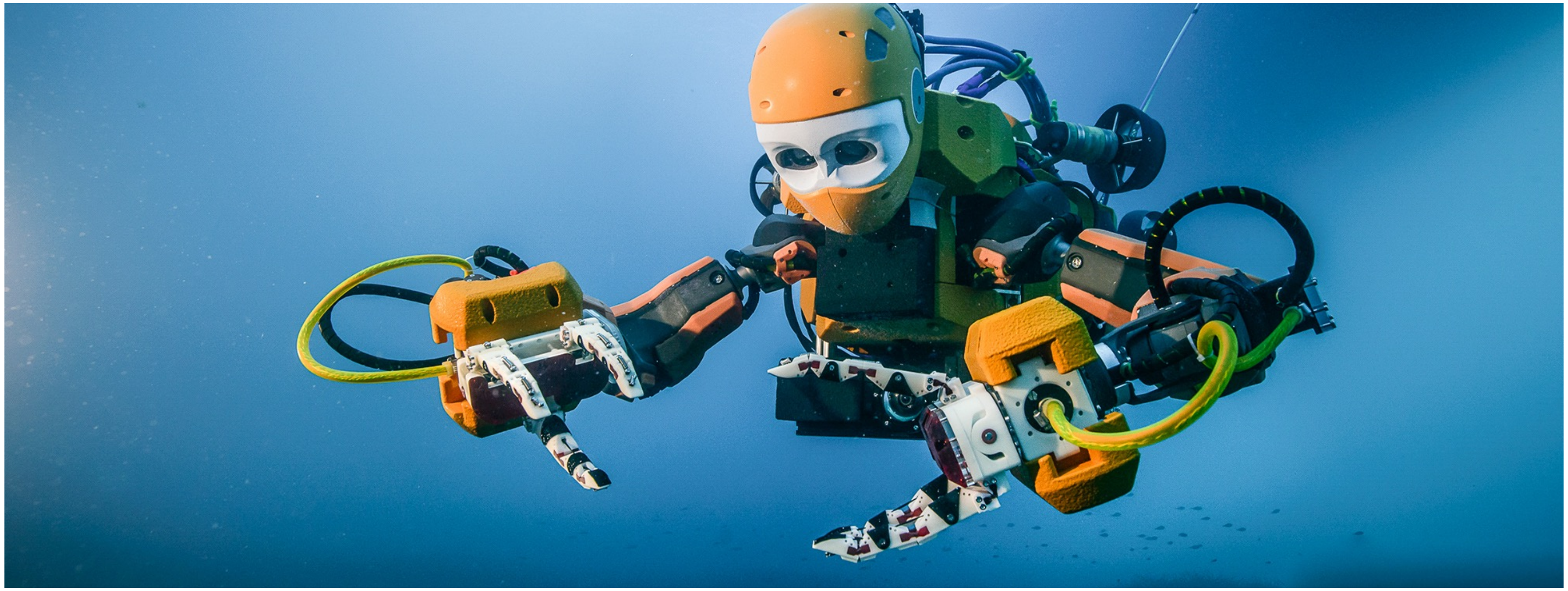








- Ocean One



- Ocean One

Ocean One

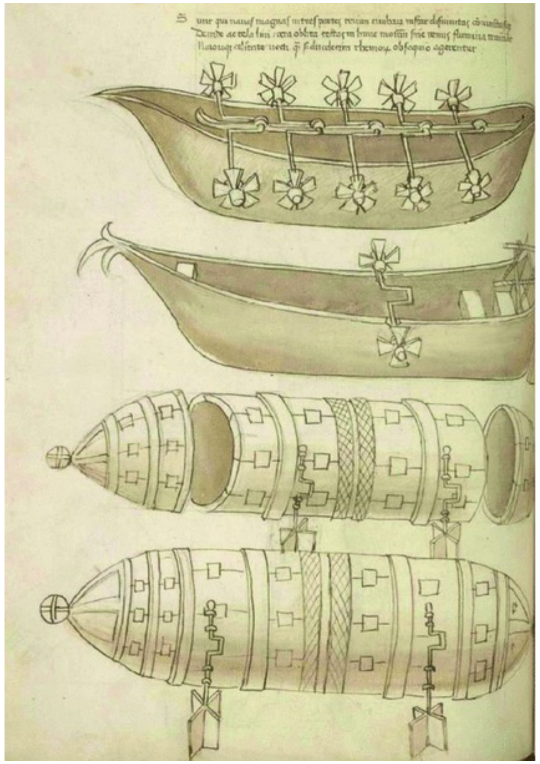
- Ocean One

https://www.youtube.com/watch?v=p1HmgP9l4VY

- Ocean One

https://www.youtube.com/watch?v=Dy5ZETdaC9k

- History
  - Maybe, the first idea of an underwater machine is from Aristotle
    - He built a machine *skaphe andros* (boat-man) that allowed Alexander the Great to stay in deep for at least half a day during the war of Tiro in 325 B.C.
  - Underwater vehicle draw by Roberto Volturio (1405—1475)
  - Leonardo da Vinci draw an underwater vehicle within the *Codex Atlanticus*, written between 1480 and 1518
- A successful story
  - In August 4, 2005, in the Pacific Seas, in front of the Kamchatka, at a depth of 200 m, a Russian manned submarine got stacked into the cables of a underwater radar
  - A British underwater vehicle, remotely piloted, cut the cables allowing the submarine to surface safely



- Acronyms
  - ROV – Remotely Operated Vehicle
    - Physically linked via a tether to an operator who can be either on a submarine or on a surface ship
    - The tether is in charge of giving power to the ROV as well as closing the manned control loop

- Acronyms
  - AUV – Autonomous Underwater Vehicle
    - Completely autonomous, relying on onboard power system and “intelligence” (sensors, controllers, actuators,…)
  - UUV - Unmanned Underwater Vehicle
    - General acronym to identify the cases above
  - UVMS – Underwater Vehicle-Manipulator System
    - UUV equipped with one or more manipulators

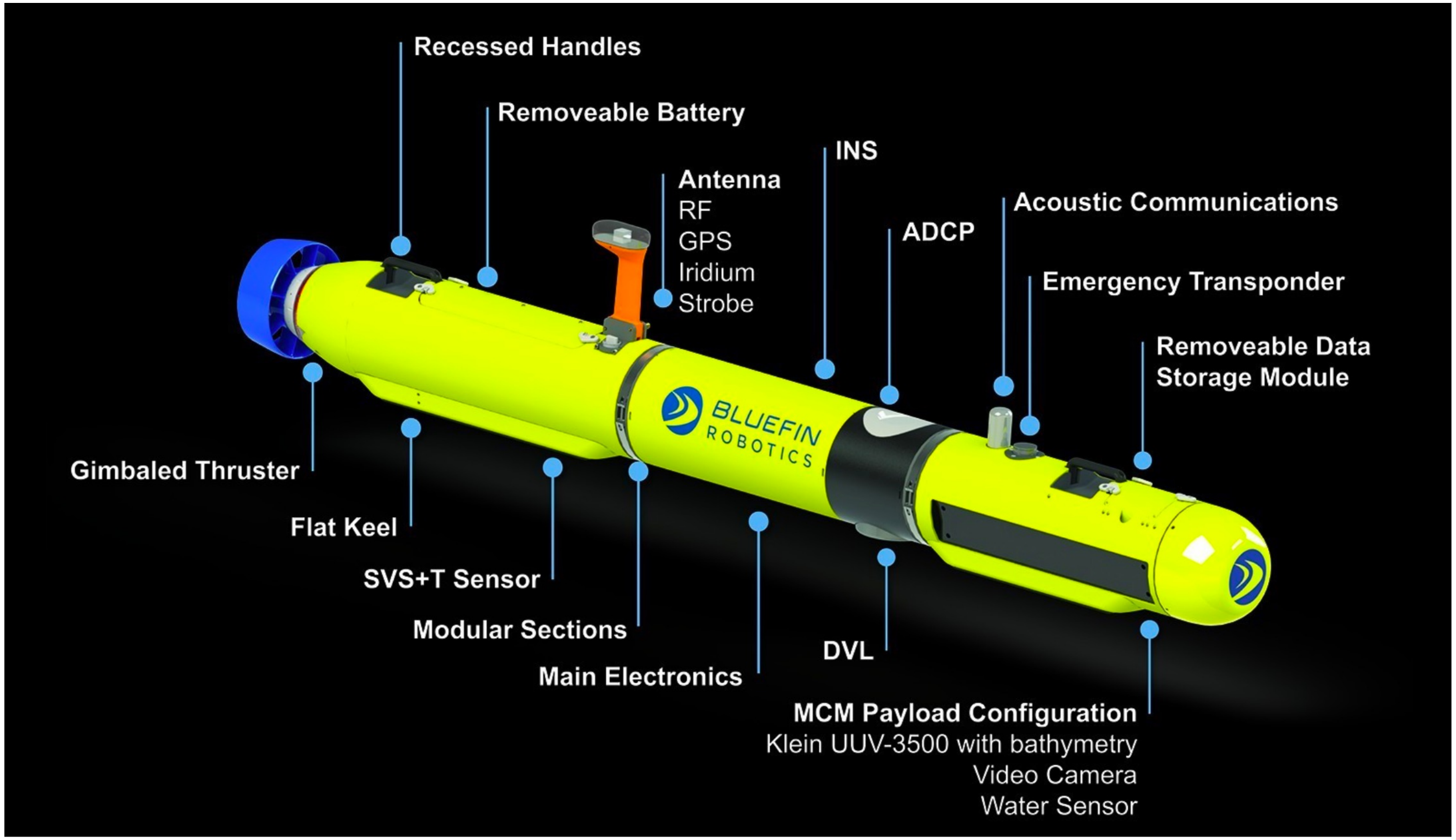
- Sensorial systems
  - The AUVs operate in hazardous environments
    - Localization problems due to absence of a single, proprioceptive sensor that measure the vehicle position and the impossibility to use GPS under the water
  - List of sensors
    - Compass
      - Gyrocompass – Geodetic north
      - Magnetic compass – Magnetic north
    - Gyroscope
      - Inertial angular rotation
    - IMU
      - Linear acceleration and angular velocity
      - The measures are combined to form estimates of the vehicle's attitude including an estimate of the geodetic north
    - Depth sensor
      - Vehicle's depth from the water pressure
    - Altitude and forward-looking sonar
      - Detect the presence of obstacles and distance from the seafloor

- Doppler velocity log (DPL)
  - By processing reflected acoustic energy from the seafloor and the water column, estimates the vehicle velocity relative to the seafloor
- Global navigation satellite system (GNSS)
  - Localize the vehicle while on the surface
- Acoustic positioning
  - Estimate vehicle's position through acoustics
- Vision system
  - Visual servoing
  - Poor visibility problem

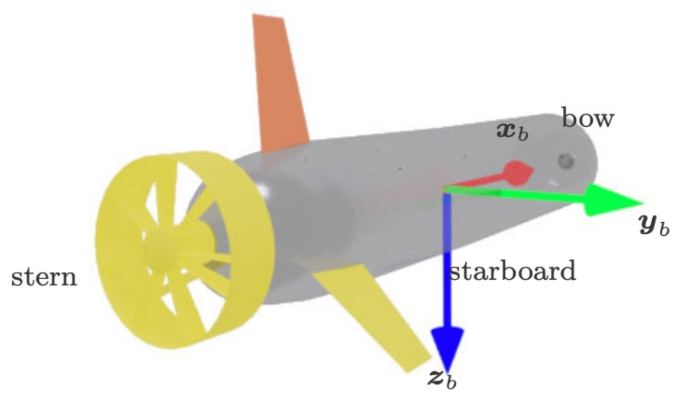
- Actuation system
  - Underwater vehicles are usually controlled by thruster and/or control surfaces

- Control surfaces
  - Rudders and sterns
  - Common in cruise vehicles (torpedo-shaped), usually used in cable/pipeline inspection
- Allocation matrix
  - Not so easy as for the UAVs
  - Highly nonlinear relationship between the force/moment acting on the underwater vehicle and the control input of the thrusters
  - Function of
    - Density of the water
    - Tunnel cross-sectional area
    - Tunnel length
    - Volumetric flowrate between input-output of the thrusters and the propeller's diameter
  - State of the thrusters described by
    - Propeller revolution
    - Induced speed of the fluid
    - Input torque
  - Thrusters are the main cause of limit cycle in vehicle positioning and bandwidth constraint

- Overall scheme



- The body frame is usually placed at the robot center of mass
- Movements
  - Surge along x_b
  - Sway along y_b
  - Heave along z_b
- Notation
  - $p_b \in \mathbb{R}^3$ position w.r.t. the world frame
  - $R_b \in SO(3)$ rotation w.r.t. the world frame
  - $\eta_b \in \mathbb{R}^3$ Euler angles for the rotation
  - $\omega_b^b \in \mathbb{R}^3$ angular velocity w.r.t. the world frame expressed in the body frame



- The dynamic model is

$$\begin{cases} m\ddot{p}_b^b = -mS(\omega_b^b)\dot{p}_b^b + f^b \\ \dot{R}_b = R_b S(\omega_b^b) \\ I_b\dot{\omega}_b^b = -S(\omega_b^b) I_b \omega_b^b + \tau^b \end{cases}$$

  - It is expressed in the body-frame without using minimal coordinate representation for the orientation
  - Notice how the gravity term is missing
    - Special care will be given to the gravity
- In matrix form, we have

$$M_{RB}\begin{bmatrix}\ddot{p}_b^b \\ \dot{\omega}_b^b\end{bmatrix} + C_{RB}\begin{bmatrix}\dot{p}_b^b \\ \omega_b^b\end{bmatrix} = \begin{bmatrix}f^b \\ \tau^b\end{bmatrix}$$

$$M_{RB} = \begin{bmatrix} mI_3 & O \\ O & I_b \end{bmatrix}, \; C_{RB} = \begin{bmatrix} mS(\omega_b^b) & O \\ O & S(\omega_b^b) I_b \end{bmatrix}$$

Added mass and inertia

- When a rigid body is moving in a fluid, the additional inertia of the fluid surrounding the body, that is accelerated by the movement of the body, has to be considered
  - This effect has been neglected in the robot seen so far, as it will be neglected for the legged robots, because the air density is much lighter than the density of the moving mechanical system
  - In underwater applications, instead, the density of the water is comparable with the density of the robot
- The fluid surrounding the robot is accelerated with the body itself
  - A force is then necessary to achieve this acceleration
  - The fluid exerts a reaction force which is equal in magnitude and opposite in direction
  - This reaction forces is the added mass contribution
- Notice that, however, the added mass is not a quantity of fluid to add to the system such that it has a bigger mass

Added mass and inertia

- The added mass effect is function of the body's geometry
- The added mass matrix associated to this effect is not necessarily positive definite
  - $M_A \in \mathbb{R}^{6\times6}$ in which usually all the elements are different from zero
  - No particular properties hold with this matrix
    - If the fluid is ideal, the UUV has low-speed velocity, if there are no currents, and if there are no waves in the sea, then M_A is symmetric and positive definite
- The added mass has also an added Coriolis and centripetal contribution
  - $C_A \in \mathbb{R}^{6\times6}$

Damping effect

- The viscosity of the fluid also causes the presence of dissipative drag and lift forces on the body
- A common simplification is to consider only quadratic damping terms and group these terms into a damping matrix
  - $D_{RB} \in \mathbb{R}^{6\times 6}$ that is positive definite
  - Usually, the coefficients of this matrix are considered as constant
- The viscous effect can be considered as the sum of two forces, the drag and the lift forces
  - The drag is parallel to the relative velocity between the body and the fluid
  - The lift force is normal to the drag one
  - Both forces are supposed to act at the body' s center of mass
- For UUVs, vortex induced forces created by the robot are often neglected
  - This does not hold in UVMs

Current effect

- Control of UUVs cannot neglect the effects of specific disturbances such as waves, wind, and Ocean current
  - Waves and wind can be neglected for completely submerged vehicles
- Ocean currents are mainly caused by
  - tidal movements,
  - atmospheric wind system over the sea
  - heat exchange at the sea's surface
  - salinity change
  - Coriolis forces due to the Earth's rotation
- Let us assume that the Ocean current expressed in the world frame and it is constant and irrotational

$$\nu_c = \begin{bmatrix} \nu_{c,x} \\ \nu_{c,y} \\ \nu_{c,z} \\ 0 \\ 0 \\ 0 \end{bmatrix} \in \mathbb{R}^6, \dot{\nu}_c = 0_6$$

Current effect

- The related effect can be added to the dynamic model of a rigid body moving in a fluid simply considering the relative velocity in the body-fixed frame

$$\nu_r = \begin{bmatrix} \dot{p}_b^b \\ \omega_b^b \end{bmatrix} - R_b^T \nu_c$$

during the derivation of of the Coriolis, centripetal, and damping terms

- When a rigid body is submerged in a fluid under the effect of gravity, two more forces must be considered with respect to the previously defined dynamic model
  - The gravitational force
  - The buoyancy
    - This is a hydrostatic effect since it is not function of the relative movement between the body and the fluid
- Define
  - $\bar{g} = [0 \quad 0 \quad g]^T \in \mathbb{R}^3$
  - $g \in \mathbb{R}$, the gravity acceleration
  - $\Delta \in \mathbb{R}$, the volume of the body
  - $\mathrm{m} \in \mathbb{R}$, the mass of the body
  - $\rho \in \mathbb{R}$, the density of the water
- The submerged weight of the body is $w = m||\bar{g}||$
- The buoyancy is $b = \rho\Delta||\bar{g}||$

- The gravity force acts at the center of mass, $r_c^b \in \mathbb{R}^3$, and it is equal to

$$f_g^b = R_b^T \begin{bmatrix} 0 \\ 0 \\ w \end{bmatrix} = R_b^T \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}$$

- The buoyancy force acts at the center of buoyancy, $r_b^b \in \mathbb{R}^3$, and it is equal to

$$f_b^b = -R_b^T \begin{bmatrix} 0 \\ 0 \\ b \end{bmatrix} = -R_b^T \begin{bmatrix} 0 \\ 0 \\ \rho \Delta g \end{bmatrix}$$

- The wrench due the gravity and buoyancy in the body-fixed frame is

$$g_{rb}^b = -\begin{bmatrix} f_g^b + f_b^b \\ S(r_c^b) f_g^b + S(r_b^b) f_b^b \end{bmatrix} \in \mathbb{R}^6$$

- The relationship between the inputs for the model-based control design

$$\tau_v = \begin{bmatrix} f^b \\ \tau^b \end{bmatrix} \in \mathbb{R}^6$$

and the control input for the thursters, $u_v \in \mathbb{R}^p$, with $p > 0$ the number of the real inputs, is highly nonlinear

- A common simplification is

$$\tau_v = B_v u_v$$

  - $B_v \in \mathbb{R}^{6\times p}$, called thrusters control matrix

Complete UUV dynamics in a matrix form

- Taking into account all the previous effects, the equations of motion of a UUV in a matrix form are

$$M_V \begin{bmatrix} \ddot{p}_b^b \\ \dot{\omega}_b^b \end{bmatrix} + (C_V + D_{RB}) \begin{bmatrix} \dot{p}_b^b \\ \omega_b^b \end{bmatrix} + g_{rb}^b = \tau_v$$

  - Considering a completely submerged UUV moving at low speed, we have
    - $M_V = M_{RB} + M_A$
    - $C_V = C_{RB} + C_A$
- Taking into account the Ocean current as well

$$M_V \begin{bmatrix} \ddot{p}_b^b \\ \dot{\omega}_b^b \end{bmatrix} + (C_V + D_{RB}) \begin{bmatrix} \dot{p}_b^b \\ \omega_b^b \end{bmatrix} + g_{rb}^b = \tau_v - \tau_{v,c}$$

  - $\tau_{v,c} \in \mathbb{R}^6$ is the effect of the Ocean current
  - M_V is symmetric
  - D_{RB} is positive definite
  - C_V is skew-symmetric

Complete UUV dynamics in a matrix form

- The dynamic model in the body frame can be written exploiting the notable property of being linear with respect to a vector of constant parameters
  - These depend on a suitable representation of the hydrodynamic terms

$$\phi_v \theta_v = \tau_v$$

  - The inclusion of the Ocean current is straightforward
  - ϕ_v regressor matrix
  - θ_v constant parameters
- It is interesting separating the contribution of the so-called restoring forces (gravity + buoyancy) and the current effects since these terms are the only forces giving a non-null contribution when the UUV is still
  - These are referred to as persistent dynamic terms
  - Considering $\tau_{v,c}$ as constant in the body frame, we have

$$M_V \begin{bmatrix} \ddot{p}_b^b \\ \dot{\omega}_b^b \end{bmatrix} + (C_V + D_{RB}) \begin{bmatrix} \dot{p}_b^b \\ \omega_b^b \end{bmatrix} + \phi_{v,r}\theta_{v,r} + \phi_{v,c}\theta_{v,c} = \tau_v$$

    - $\phi_{v,r}\theta_{v,r}$ regressor and constant parameters referred to the restoring forces
    - $\phi_{v,c}\theta_{v,c}$ regressor and constant parameters referred to the Ocean current

Complete UUV dynamics in a matrix form

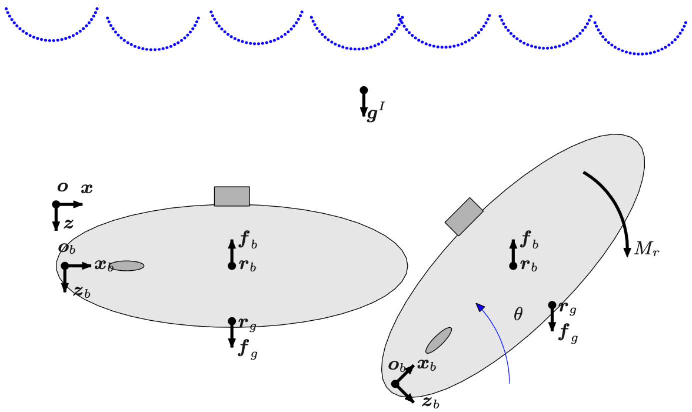
- The previous form can be rewritten as

$$M_V \begin{bmatrix} \ddot{p}_b^b \\ \dot{\omega}_b^b \end{bmatrix} + (C_V + D_{RB}) \begin{bmatrix} \dot{p}_b^b \\ \omega_b^b \end{bmatrix} + \phi_{v,p}\theta_{v,p} = \tau_v$$

  - $\phi_{v,p}\theta_{v,p} = \phi_{v,r}\theta_{v,r} + \phi_{v,c}\theta_{v,c}$
  - $\phi_{v,p} = \begin{bmatrix} R_b^T e_3 & O & I_3 & O \\ 0_3^T & S(R_b^T e_3) & O & I_3 \end{bmatrix}$
  - $\phi_{v,p} = \begin{bmatrix} R_b^T e_3 & O & R_b^T & O \\ 0_3^T & S(R_b^T e_3) & O & R_b^T \end{bmatrix}$, this if the Ocean current is considered constant in the world frame (better fits than considering constant in the body frame)

Discussion

- Among the hydrodynamic effects acting on a rigid body moving in a fluid, the restoring forces and the Ocean current are the major concern in designing a motion control law for a UUV
- Adaptive controllers well handle the compensation of restoring forces
  - The importance of restoring forces can be appreciated in large dimension vehicles where small displacements of the center of mass and the center of buoyancy generates large thrusts for compensate for them



- Another problem arises since the restoring forces are well represented in the body frame, while the Ocean current in the fixed frame