Abstract: This paper deals with $\mathcal{L}_1$ adaptive control of a novel omnidirectional underwater vehicle called MEROS. To the best of our knowledge, this is the first study of depth and attitude (i.e. $\phi$, $\theta$, and $\psi$) tracking control on an underwater vehicle. We experimentally prove the effectiveness of the proposed control approach by commanding in closed-loop simultaneously the four aforementioned degrees of freedom (DoFs). The dynamic model of MEROS is highly nonlinear with coupling effects between the different DoFs making its stabilization and tracking control more challenging than conventional ROVs (remotely operated vehicles). Therefore, the use of a robust controller becomes essential, and the proposed scheme allows to ensure robustness whilst fast adaptation is achieved. Real-time experiments are performed to show the effectiveness of the proposed control design.

Keywords: Underwater robot, Mechatronic systems, Motion Control, Autonomous robotic systems, Attitude control, Robotics technology, $\mathcal{L}_1$ adaptive control.

1. INTRODUCTION

During the last decades, small and medium ROVs, able to perform complex inspection tasks are getting an increasing attention in many applications including ship hull inspection, scientific and archaeological researches, aquaculture farms, dams and wind parks inspection, and also military applications. For those tasks, the need of a sophisticated control solution in order to successfully perform the aforementioned mission is of high interest. Typically, the robot should be able to follow a desired reference trajectory autonomously in spite of external disturbances and parametric uncertainties.

Different advanced control techniques have been proposed so far in the literature in order to perform this objective. One can cite nonlinear PID control Guerrero et al. (2020b), model predictive control Molero et al. (2011), robust $\mathcal{H}_\infty$ control Roche et al. (2011), sliding mode control Pisano and Usai (2004); Shehu Tijjani et al. (2021), intelligent control Chang and Liu (2003), adaptive control Maalouf et al. (2015a), inverse dynamics control Salumae et al. (2016), and data-fusion control Remmas et al. (2021). These studies highlighted two important points related to underwater vehicles control. First, their dynamic models are difficult to identify because of their inherent nonlinearities and their evolution in a changing environment (salinity, buoyancy, currents, etc.). The second point is related to the robustness which is an important issue (persistent presence of external disturbances, unknown parameters, unprecise estimation). This motivates the development of adaptive controllers for such systems by many authors Guerrero et al. (2020a); Shehu Tijjani et al. (2021); Sun and Cheah (2009); Zhao and Yuh (2005). In these studies, the presented controllers have some drawbacks such as: a) the necessity of an adequate parameter initialization depending on the system configuration, we loose then the intuitiveness in the control tuning b) the increase in the adaptation gains that may lead to instability Antonelli (2007) and therefore, a compromise with good performances has to be found, and c) The need for the persistency in excitation can lead to a bad transient behaviour. To avoid the aforementioned drawbacks in adaptive control, Hovakimyan and Cao (2010) proposed $\mathcal{L}_1$ adaptive control in order to guarantee robustness performances decoupled from adaptation. Indeed, it has the major advantage of ensuring good performances without any need of appropriate parameter initialization as it was shown on a small ROV in Maalouf et al. (2012, 2015b) for only 2 DoFs.

In most of the mentioned studies, the authors presented either only simulation results Fjelstad and Fossen (1994); Li et al. (2004); Perrier and Canudas-De-Witt (1996); Roche et al. (2011); Sun and Cheah (2009) or real-time experiments on one DoF close-loop control Smallwood and Whitcomb (2002) Molero et al. (2011) or two DoFs Kreuzer (1996); Steenson et al. (2012). Some authors presented a simultaneous control of position ($x$, $y$ and $z$) Yuh and Nie (2000), and others presented position and yaw control Hoang and Kreuzer (2008), or in some cases a stabilization of pitch and roll is added without any change in the desired attitude Zhao and Yuh (2005). According to our best knowledge, this is the first study presenting trajectory tracking of attitude (yaw pitch roll) which is necessary for complex inspection tasks.

The depth ($z$) is also controlled in closed-loop and the two remaining translational degrees of freedom ($x$ and $y$ for surge
### 2. DESCRIPTION AND MODELLING OF MEROS UNDERWATER VEHICLE

#### 2.1 Description of the underwater vehicle MEROS

MEROS is a six-degree-of-freedom omnidirectional underwater vehicle controlled by six thrusters Izard et al. (2015). It is shown in figure 1. It has been designed for inspection tasks up to 100m of maximum depth. It is a mini-ROV that can be carried by one operator as it has a weight of only 13Kg. Four degrees of freedom are controlled in closed loop (depth, roll, pitch, yaw), the two remaining degrees of freedom (translation X and Y) being controlled with a gamepad in open loop by the operator.

![Fig. 1. General view of MEROS underwater vehicle.](image)

MEROS was inspired from Pierrot et al. (1998) but adapted after some simulations (using Solidworks Flow Simulation) in order to limit the hydrodynamic effects between the thrusters. Two sensors are used: a pressure sensor (Series 33X from Keller) for depth and an inertial measurement unit (MTi from Xsens) for getting the orientation and the angular velocities. The IMU is the only sensor that may give data (acceleration) that Coriolis terms can be neglected and integration does not give error. As in Maalouf et al. (2015b), and as the final use of the robot will be for inspection tasks a relatively low velocity, we assume that Coriolis terms can be neglected $\dot{C}(v)\approx 0$ leading to:

$$M\ddot{v} + C(v)\dot{v} + D(v)\dot{v} + g(\eta) = \tau + \omega_d$$

where $M \in \mathbb{R}^{6 \times 6}$, $C \in \mathbb{R}^{6 \times 6}$ and $D \in \mathbb{R}^{6 \times 6}$ represent respectively the inertia (including added mass), Coriolis-Centripetal forces, and damping. $g$ is the vector of weight and buoyancy. $\tau \in \mathbb{R}^{6 \times 1}$ represents the vector of the control inputs and $\omega_d \in \mathbb{R}^{6 \times 1}$ represents external disturbances. As in Maalouf et al. (2015b), and as the final use of the robot will be for inspection tasks a relatively low velocity, we assume that Coriolis terms can be neglected $\dot{C}(v)\approx 0$ leading to:

$$M\ddot{v} + D(v)\dot{v} + g(\eta) = \tau + \omega_d$$

Equation (5) expresses the dynamics in the body-fixed frame, and it can be transformed in the earth-fixed frame using the following transformations Fossen (2002):

$$\dot{\eta} \approx J(\eta)v$$

$\eta$ is the vector of cartesian positions and Euler angles in the earth-fixed frame space, $v$ is the vector of velocities in the body-fixed frame and $J(\eta) \in \mathbb{R}^{6 \times 6}$ represents the jacobian transformation matrix mapping the body and earth-fixed frames.

![Fig. 2. Illustration of the reference frames of MEROS (xe, ye, ze: earth-fixed frame, xb, yb, zb: body-fixed frame).](image)
\[
\begin{align*}
\ddot{\eta} &= J(\eta)v \\
\dot{\eta} &= J(\eta)\dot{v} + \dot{J}(\eta)v \\
M(\theta)^* = J^{-T}(\eta)MJ^{-1}(\eta) \\
D^*(v, \eta) &= J^{-T}(\eta)D(v)J^{-1}(\eta) \\
g^*(\eta) &= J^{-T}(\eta)g(\eta) \\
\tau^* &= J^{-T}(\eta)\tau_d \\
\omega_d &= J^{-T}(\eta)\omega_d
\end{align*}
\]

with \(J^{-T} = (J^{-1})^T\). The vehicle’s dynamics in the earth-fixed frame can be expressed as follows:

\[
M^*(\eta)\ddot{\eta} + D^*(v, \eta)\dot{\eta} + g^*(\eta) = \tau^* + \omega_d
\]

The general model (7) describes the dynamics of the vehicle in its full six DoFs. In our case, as only four DoFs are studied and controlled in close loop, it is possible to extract from (7) the equations of interest in order to obtain a reduced model in the earth-fixed frame:

\[
\begin{bmatrix}
M_z^* & 0 & 0 & 0 \\
0 & M_z^* & 0 & 0 \\
0 & 0 & M_z^* & 0 \\
0 & 0 & 0 & M_z^*
\end{bmatrix}
\begin{bmatrix}
\dot{\theta} \\
\dot{\phi} \\
\dot{\psi} \\
\dot{\omega}_d
\end{bmatrix}
+ \\
\begin{bmatrix}
D_z^* & 0 & 0 & 0 \\
0 & D_z^* & 0 & 0 \\
0 & 0 & D_z^* & 0 \\
0 & 0 & 0 & D_z^*
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta} \\
\ddot{\phi} \\
\ddot{\psi} \\
\ddot{\omega}_d
\end{bmatrix}
+ \\
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\tau_\phi^* + \omega_d \dot{\phi} \\
\tau_\theta^* + \omega_d \dot{\theta} \\
\tau_\psi^* + \omega_d \dot{\psi}
\end{bmatrix}
\]

where \(M_z^*, M_z^*, M_z^*, M_z^*\) and \(M_z^*\) are the mass parameters in the earth-fixed frame related to the degrees of freedom depth (Z), roll (\(\phi\)), pitch (\(\theta\)) and yaw (\(\psi\)). \(D_z^*, D_z^*, D_z^*\) and \(D_z^*\) are the damping parameters in the earth-fixed frame for these four degrees of freedom as well. The matrices of mass and damping are considered diagonal because of the spherical shape of the vehicle (cf. figure 1 and 2). The terms \(g_{\phi}^*, g_{\theta}^*, g_{\psi}^*, \omega_d\) for \(i = z, \phi, \theta\) and \(\psi\), represent respectively the weight/buoyancy components, the vector of control inputs and the external disturbances in the earth-fixed frame.

3. PROPOSED \(\mathcal{L}_1\) ADAPTIVE CONTROL SOLUTION

3.1 Background on \(\mathcal{L}_1\) Adaptive control

The \(\mathcal{L}_1\) Adaptive control has been proposed by Hovakimyan and Cao (2010) and was applied to the control of a two degrees of freedom ROV in Maalouf et al. (2013, 2015b). In this paper, and as mentioned before, we propose a more challenging problem which is the depth and attitude control of MEROS underwater vehicle presented in section 2. This controller can guarantee the fast convergence and the robustness at the same time. Its control architecture is illustrated in the block-diagram of Fig. 3. It includes four parts: the controlled system, the state predictor, the adaptation phase and the control law with a low pass filter. The role of the low pass filter is to cancel out the high frequencies that might occur in the control input which ensures a fast adaptation without altering the robustness. The details of each block in Fig. 3 are presented in the sequel:

- **Controlled system:**
  Let us consider a class of nonlinear systems in which our system belongs to:

\[
x(t) = d(x(t), u(t)) + \xi(t)
\]

where \(d(x, u)\) is a known full rank constant matrix and \(\xi(t)\) is the measured output.

- **State predictor:**
  The form of the state predictor is the same as the controlled system. It can be written as:

\[
h(t) = Cx(t)
\]

- **Adaptation:**
  Let us consider a class of nonlinear systems in which our system belongs to:

\[
x(t) = \sum_{i=1}^{n} \alpha_i(t) g_i(x(t)) + \sum_{i=1}^{m} \beta_i(t) \sigma_i(t) + \eta(t)
\]

where \(\alpha_i(t), \beta_i(t)\) and \(\sigma_i(t)\) are known functions of time.

Fig. 3. Block diagram of the architecture based on the \(\mathcal{L}_1\) adaptive controller Hovakimyan and Cao (2010).
These parameters are estimated using the error between the controlled system and the state predictor, and a projection operator is used to ensure their boundedness. The adaptation law of each estimated parameter is written as follows:

\[
\dot{\theta}(t) = \Gamma \text{proj} \hat{\theta}(t), - (\ddot{z}(t) TP B_m) \|x(t)\|_{L_\infty} \\
\dot{\sigma}(t) = \Gamma \text{proj} \hat{\sigma}(t), -(\ddot{z}(t) TP B_m)^T \\
\dot{\omega}(t) = \Gamma \text{proj} \hat{\omega}(t), -(\ddot{z}(t) TP B_m) u_m^T(t)
\]

\[
\Gamma \text{ is the adaptation gain and } \ddot{z}(t) = \ddot{x}(t) - x(t) \text{ is the prediction error. } P \text{ is the solution of the algebraic Lyapunov equation: } A_m^T P + P A_m = -Q \text{ for any arbitrary symmetric positive definite matrix } Q = Q^T > 0.
\]

- Control law with low pass filter:

The control input \(u_a\) is calculated with a low pass filter. It takes the following form in the Laplace domain:

\[
u_a(s) = -k D(s) \tilde{U}(s) - k_p r
\]

\[
\tilde{U}(s) = \omega u_a + \theta(t) \|x(t)\|_{L_\infty} + \sigma(t)
\]

\[
\omega = \begin{bmatrix} \eta_1, \eta_2, \eta_3, \eta_4 \end{bmatrix}^T, \sigma = \begin{bmatrix} \eta_1, \eta_2, \eta_3, \eta_4 \end{bmatrix}^T.
\]

In this equation, \(\eta_1 = [\varphi \; \psi]^T, \eta_2 = [\dot{\varphi} \; \dot{\psi} \; \dot{\theta} \; \dot{\psi}]^T\), and we consider \(\omega \in \mathbb{R}^{4 \times 4}\) being an identity matrix (we assume that we have a good knowledge of the characteristics of the vehicle thrusters). \(D^*_m\) is a diagonal matrix with the following form:

\[
\begin{bmatrix}
0_{4 \times 4} & I_4 \\
0_{4 \times 4} & 0_{4 \times 4}
\end{bmatrix} = \begin{bmatrix}
0_{4 \times 4} & I_4 \\
0_{4 \times 4} & 0_{4 \times 4}
\end{bmatrix}
\]

The same with \(\eta_1, \eta_2, \eta_3, \eta_4\). If we write equation (16) into the form of equation (11) with the state matrix \(A_m\), we can obtain:

\[
y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix} \eta_1 \\
\eta_2 \\
\eta_3 \\
\eta_4
\end{bmatrix} = \begin{bmatrix} z \\
\varphi \\
\theta \\
\psi
\end{bmatrix}
\]

In this equation, \(A_m \in \mathbb{R}^{8 \times 8}\) is a Hurwitz matrix obtained with \(k_m\). \(B_m = 0_{4 \times 4} \in \mathbb{R}^{8 \times 4}, \theta \in \mathbb{R}^4\) includes the uncertainties damping coefficients, with \(\theta = [\Delta(-D^*_z), \Delta(-D^*_y), \Delta(-D^*_\theta), \Delta(-D^*_\psi)]^T\) (\(\Delta\) refers to the uncertainty), \(\sigma \in \mathbb{R}^4\) includes the weight and buoyancy as well as the external disturbances, with \(\sigma = [-g^*_z + \omega^*_z, -g^*_y + \omega^*_y, -g^*_\theta + \omega^*_\theta, -g^*_\psi + \omega^*_\psi]^T\).

\[
\|\eta(t)\|_{L_\infty} \text{ is the infinity norm of the state vector } \eta \text{ at instant } t.
\]

The control input \(u = u_m + u_a\) is computed in the earth fixed frame. The system outputs are \(Z, \varphi, \theta\) and \(\psi\).

4. Obtained Real-Time Experimental Results

In this section, the obtained experimental results are presented and discussed. The tests have been performed in a 5 m³ pool without any input from the human user during the motions (i.e. autonomous mode). A large part of the umbilical is deployed in order to avoid any drag effect on the ROV. The reference tracking trajectory of each degree of freedom is described as follows: for \(Z\), from \(t = 0\) to \(t = 15\) s, the depth decreases with \(15\) cm. at \(t = 30\) s, the depth continues to fall \(20\) cm. and remains at this value until \(t = 210\) s, then the depth decreases \(20\) cm. For \(\varphi\), at \(t = 70\) s, the roll desired values rises by \(30°\) and remains at this value until \(t = 150\) s, the desired roll returns to the initial value. For \(\theta\), at \(t = 50\) s, the pitch order steps up \(15°\) and stays in this value until \(t = 130\) s, and then, it returns to its initial value. For \(\psi\), at \(t = 100\) s, the desired yaw increases by \(30°\) and stays in this value until \(t = 170\) s, the desired yaw returns to its initial value. The autonomously non-controlled DoFs (i.e. surge and sway) can be controlled in open loop by the human during shared control, where an interaction (due to the coupling in dynamics) is noticed. The values of the tuned parameters (through numerical simulations first, then finely adjusted during experiments) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Degree of freedom</th>
<th>Poles</th>
<th>(\Gamma)</th>
<th>(k)</th>
<th>(D(s))</th>
<th>Initial values (\hat{\theta}(0)) and (\hat{\sigma}(0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z)</td>
<td>((-7, -3))</td>
<td>(10000)</td>
<td>(2)</td>
<td>(\frac{1}{3})</td>
<td>(0)</td>
</tr>
<tr>
<td>(\varphi)</td>
<td>((-7, -4))</td>
<td>(45)</td>
<td>(1)</td>
<td>(\frac{1}{3})</td>
<td>(0)</td>
</tr>
<tr>
<td>(\theta)</td>
<td>((-7, -3))</td>
<td>(80)</td>
<td>(2)</td>
<td>(\frac{1}{3})</td>
<td>(0)</td>
</tr>
<tr>
<td>(\psi)</td>
<td>((-7, -4))</td>
<td>(30)</td>
<td>(1.6)</td>
<td>(\frac{1}{3})</td>
<td>(0)</td>
</tr>
</tbody>
</table>

The results are presented in Fig. 5. We can observe in this scenario, that when four degrees of freedom are controlled, there are some oscillations that are more significant for the pitch and yaw angles. This can be due to the effect of the umbilical that introduces external torques due to its weight and the torsion brought by the high roll desired angle. We also observe that these oscillations are more significant when there is a change in the desired trajectory of another DoF and this is logically due to the isotropic design of MEROS and the coupling effect. In general, when the four DoFs are controlled simultaneously we expect more hydrodynamic effects (even if the design was optimized to limit them) and this may have an additional disturbing effect. In terms of control inputs, there are no saturation effects. We also suppose that the numerical derivative used in the estimation of the velocities can be replaced by an observer in order to avoid the possible amplification of the measurement noise.
Fig. 4. Detailed block-diagram of the $\mathcal{L}_1$ adaptive controller architecture Hovakimyan and Cao (2010).

Fig. 5. Obtained real-time experimental results: Simultaneous control of depth, roll, pitch and yaw. (Left) evolution versus time of the controlled degrees of freedom w.r.t their respective reference trajectories, (Middle) evolution of their corresponding control inputs, (right) evolution versus time of the estimated parameters.
5. CONCLUSION AND FUTURE WORK

This paper deals with the control of an omnidirectional underwater vehicle. The proposed control solution, based on $L_1$ adaptive control, has been experimentally validated for 4 DOFs (attitude and depth). Another interesting result is the ability of such a robust control to manage the strong couplings due to the isotropic design of the robot. These results have been obtained despite the relatively simplified model and this proves the effectiveness and robustness of the proposed $L_1$ adaptive control. In the future, we would like to consider some enhancements through the use of the quaternion representation and take full advantage of the omnidirectional possibilities during inspection tasks. Furthermore, we observed that the umbilical of the robot is too stiff and may have a destabilizing effect on the vehicle (oscillations). Consequently, a new design of the umbilical can be planned. Besides, further tests and experiments will be performed in open water, with real operating conditions like dam or harbor inspection in order to confront the ROV to more realistic challenging applications.

REFERENCES


