Model reference sliding mode control of underwater vehicle-manipulator systems

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Abstract. UVMS consisting of the underwater vehicle and underwater manipulator is a dynamically coupled system. The movement of the underwater manipulator has a great impact on the stability of the underwater vehicle. A control scheme combining robust feedback control of the vehicle and feed forward compensation of the manipulator is proposed. First, the dynamic modelling of UVMS by Newton-Euler method is presented and used to obtain compensation. And then, we designed a sliding mode controller with the compensation. Finally, computer physics simulations are performed to investigate the effectiveness of this scheme in stability.

1. Introduction

Autonomous underwater vehicles (AUVs) have been developed for different marine applications, such as oceanographic research, mapping, exploring oil and so on, which are limited to collecting sensor data and generating maps. With the deepening of marine development and exploration, AUVs are equipped with one or more manipulators to gain intervention capabilities for desired tasks such as sampling, maintenance, handling and so on. This kind of AUV is called autonomous underwater vehicle-manipulator systems (UVMSs) [1-3]. UVMS is a highly redundant, non-linear, coupled multi-degrees of freedom mechanical system. The dynamic coupling has always been a major factor affecting the stability and accuracy of UVMS control. Therefore, it is significant to do researches on dynamic modelling and robust, stable and accurate coordinated control for UVMS.

For developing accurate control of UVMS, many research institutes have studied the dynamical modeling of UVMS. The first attempt for modelling UVMS dynamics was to build a model in closed form by Newton-Euler method for the development of simulation control algorithm [4]. Nilanjan Sarkar et al used Quasi-Lagrange approach to model UVMS for developing a motion coordination algorithm that could make the total drag effect on the system minimized with UVMS reaching desired trajectories [5]. T.J. TARN et al proposed a dynamic model for UVMS through Kane’s method and this method provides a straightforward approach for incorporating external forces into model [6]. Besides, some researchers focused their attention on estimation of hydrodynamic parameters. Fossen [7] summed up the hydrodynamic parameters about underwater vehicle in detail. McLain et al [8] proposed a hydrodynamic modeling method for underwater manipulators and verified it experimentally. In addition to researches on modelling, there are many studies on robust control of UVMS. Non-model-based control schemes have been widely used due the complexity of underwater environment. An impedance control scheme for the UVMS was investigated and it allows UVMS to interact with the environment in stable and accurate manner [9]. A PID-based control scheme was used in the real UVMS RobCutt-II for accurate 3D helical path tracking [10 11]. A model-free force-
motion control based on second-order sliding modes was proposed and used on the simulation of the famous UVMS platform VORTEX-PA10 [12]. Some researchers make use of dynamic model to the control design. Based on model, a model reference adaptive controller was proposed [13].

This paper presents a model reference sliding mode control scheme. In section 2, the dynamics of the UVMS is built by the Newton-Euler method. Forces and moments from manipulator to vehicle are modelled, which is used for the compensation for control. In section 3, the control scheme is discussed in detail. We present a sliding mode controller that is not sensitive to parameter variations and rejection of disturbances. Due to the existence of the strong coupling between the vehicle and the manipulator, the movement of the manipulator and environmental impact on the manipulator will indirectly affect the stability of the vehicle, so we model dynamics to get forces and moments of manipulator on vehicle and use them to compensate control of vehicle for improving tracking stability and accuracy. In section 4, based on the UVMS designed by lab, computer physics simulations of the Webots are presented for performance of the control scheme. Finally, section 5 holds conclusions.

![Figure 1. Coordinate frame arrangement of UVMS.](image)

2. Dynamic modelling

2.1. Dynamic Model of the underwater vehicle

The dynamics on the underwater vehicle as shown in figure 1 is modeled through the Newton-Euler formulation and its equation of motion can be expressed as:

\[ M\ddot{\mathbf{v}} + C(\mathbf{v})\dot{\mathbf{v}} + D(\mathbf{v})\mathbf{v} + \mathbf{g}(\mathbf{\eta}) = \mathbf{\tau}_p + \mathbf{\sigma}_M + \mathbf{\sigma}_D \]  

(1)

\[ M = M_{RB} + M_A, \quad C(\mathbf{v}) = C_{RB}(\mathbf{v}) + C_A(\mathbf{v}), \quad \dot{\mathbf{\eta}} = \mathbf{J}(\mathbf{\eta})\mathbf{v} \]

(2)

\( M_{RB} \) and \( M_A \) are the rigid body mass matrix and the added mass matrix. \( C_{RB}(\mathbf{v}) \) and \( C_A(\mathbf{v}) \) are the rigid body Coriolis and centripetal matrix and added Coriolis and centripetal matrix. \( D(\mathbf{v}) \) is the drag matrix and \( \mathbf{g}(\mathbf{\eta}) \) is the vector of gravity and buoyancy forces and moments. \( \mathbf{\tau}_p \) is the vector of propulsion forces and moments. \( \mathbf{v} = [u, v, w, p, q, r]^T \) is the vector of linear and angular vector with coordinates in the vehicle frame. \( \mathbf{\eta} = [x, y, z, \phi, \theta, \psi]^T \) is the position and orientation vector with coordinates in the inertial frame, the orientation part is represented in Euler angles. \( \mathbf{\sigma}_M \) is the vector of forces and moments from the manipulator to the vehicle and \( \mathbf{\sigma}_D \) is the vector of disturbances. \( \mathbf{J}(\mathbf{\eta}) \) is the kinematic transformation matrix. [7]
2.2. Dynamic Model of the underwater manipulator for compensation

The dynamics of the 2 DOF underwater manipulator as shown in figure 1 is modelled by the recursive Newton-Euler algorithm. The velocity and acceleration of the links are calculated iteratively from the inner link to outer link, whose interactions are as follows:

\[
\begin{align*}
\dot{\omega}_{i+1} &= R_{i}^{i+1} \dot{\omega}_i + \dot{\theta}_{i+1} \dot{Z}_{i+1} \\
\ddot{\omega}_{i+1} &= R_{i}^{i+1}(\dot{\omega}_i \times \dot{\theta}_{i+1}) + \dot{\theta}_{i+1} \dot{Z}_{i+1} \\
\dot{\upsilon}_{i+1} &= R_{i}^{i+1}(\dot{\upsilon}_i + \dot{\omega}_i \times \dot{p}_i) \\
\ddot{\upsilon}_{i+1} &= R_{i}^{i+1}(\dot{\upsilon}_i + \dot{\omega}_i \times \ddot{p}_i + \dot{\omega}_i \times (\dot{\omega}_i \times \dot{p}_i)) \\
\dot{C}_{i+1} &= R_{i}^{i+1}(\dot{\upsilon}_i + \dot{\omega}_i \times \dot{p}_i + \dot{\omega}_i \times (\dot{\omega}_i \times \dot{p}_i)) + \dot{\omega}_i \times \dot{C}_{i+1} \\
\dot{I}_{i+1} &= R_{i}^{i+1}(\dot{\upsilon}_i + \dot{\omega}_i \times \dot{p}_i + \dot{\omega}_i \times (\dot{\omega}_i \times \dot{p}_i)) + \dot{\omega}_i \times \dot{I}_{i+1} \\
\ddot{Z}_i &= [0 \ 0 \ 1]^T
\end{align*}
\]

The interactions of forces and moments between two adjacent links are as follows:

\[
\begin{align*}
\dot{F}_i &= iR^{i+1} f_{i+1} + \dot{F}_i + p_i + m_i g_i + b_i \\
\dot{N}_i &= iR^{i+1} n_{i+1} + iP_{i+1} \times (iR^{i+1} f_{i+1}) + iN_i + iP_{Cl} \times (iF_i + p_i + m_i g_i) + iP_{bi} \times b_i
\end{align*}
\]

\(i\dot{\omega}_i\) and \(i\upsilon_i\) are the linear velocity and the angular velocity vector of the link \(i\). \(iR\) is the rotation matrix. \(\dot{\theta}_i\) is the angular velocity of the joint \(i\). \(iP_{i+1}\) is the vector from joint \(i\) to joint \(i+1\). \(iP_{Cl}\) and \(iP_{bi}\) are vectors from center of gravity and center of buoyancy for the link \(i\). \(iF_i\) and \(iN_i\) are vectors of total forces and moments acting at the center of mass of the link \(i\). \(i\dot{\omega}_i\) is the acceleration vector of the center of gravity, \(m_i\) is the mass of the link \(i\). Each link is assumed as the cylinder with radius \(r_i\) and length \(l_i\), so the mass and added mass of the link \(i\) is \(M_i = diag[1.1 m_i, m_i + \pi r_i^2 m_i, m_i + \pi r_i^2]\) and the moment of inertia and added moment of matrix of the link \(i\) is \(I_i = diag[I_{11}, I_{12} + \pi r_i^2 l_i / 12, I_{13} + \pi r_i^2 l_i^2 / 12]\). \(p_i\) is the hydrodynamic friction forces. \(i\dot{f}_i\) and \(i\dot{n}_i\) are forces and moments on the joint \(i\). \(m_i g_i\) is the vector of gravity of the link \(i\) and \(b_i\) is the vector of buoyancy of the link \(i\).

According to the above analysis, with the motion states such as the vehicle and the angle, velocity and acceleration of each joint, \(\dot{F}_i\) and \(\dot{N}_i\) of each link are obtained by the iteration from the inside out. And then, forces \(\dot{f}_0\) and moments \(\dot{n}_0\) on the vehicle base frame \(\{0\}\) from the manipulator are obtained from the outside in. Therefore, forces and moments from the 2 DOF manipulator on the vehicle frame \(\{B\}\) are as follows:

\[
\sigma_M = [\sigma_{Mf}^{0} \sigma_{Mn}^{0}] = \left[\begin{array}{c} bR^{0} f_0 \\ pR^{0} n_0 - d_0 \times \sigma_{Mf}^{0} \end{array} \right]
\]

\(bR\) is the rotation matrix from the base frame \(\{0\}\) to the vehicle frame \(\{B\}\). \(b d_0\) is the position vector of the manipulator base point \(\{0\}\) in the vehicle frame \(\{B\}\).

3. Control scheme

3.1. Sliding mode controller

The trajectory \(\eta\) is required to track desired trajectory \(\eta_{d}\) in the inertial frame. For the convenience of designing the controller, we transform direction of the state \(\eta\) and \(\eta_{d}\) from inertial frame to vehicle frame.

\[
\eta_v = J(\eta)^{-1} \eta, \quad \eta_{vd} = J(\eta)^{-1} \eta_d
\]
The underwater vehicle system is divided into 6 subsystems and the error of the $i$-th subsystem is as:

$$ E_{vi} = \begin{bmatrix} \eta_{vi} \\ \dot{\eta}_{vi} \end{bmatrix} - \begin{bmatrix} \eta_{vdil} \\ \dot{\eta}_{vdil} \end{bmatrix} = \begin{bmatrix} e_{vi} \\ \dot{e}_{vi} \end{bmatrix} \tag{7} $$

Linear time-invariant sliding surface is as:

$$ s_i = C_i^T E_{vi} = c_i e_{vi} + \dot{e}_{vi} \tag{8} $$

where $C_i = [c_i \ 1]^T$ and is chosen to guarantee stable sliding motion. Considering the form of switching control [14], the switching control algorithm is as follows:

$$ u_i = -\Psi_i^T E_{vi} - \delta_i \text{sign}(s_i) \tag{9} $$

where $\delta_i > 0$ is a relay gain, $\Psi_i = [\psi_{i1}, \psi_{i2}]^T$ are the switching feedback gains and as follows:

$$ \psi_{i1} = \begin{cases} \alpha_{i1} & s_i e_{vi} > 0 \\ \beta_{i1} & s_i e_{vi} < 0 \end{cases} \quad \psi_{i2} = \begin{cases} \alpha_{i2} & s_i \dot{e}_{vi} > 0 \\ \beta_{i2} & s_i \dot{e}_{vi} < 0 \end{cases} \tag{10} $$

For the reachability of this sliding surface, the condition should be $s_i \dot{s}_i < 0$.

$$ \dot{s}_i = c_i \dot{e}_{vi} + h_{ii} u_i + \sum_{j=1, j \neq i}^{6} h_{ij} u_j + f_i - 3 \tilde{\eta}_{vdil} \tag{11} $$

$h_{ij}$ is constant in the $H = M^{-1}$ by transformation equation (6) and $f_i$ is treated as a limited disturbance. We can find $\Psi_i$ and $\delta_i$ in $u_i$ by the method in [15] to ensure that $s_i \dot{s}_i$ is less than zero.

In order to suppressing chattering, the sign function $\text{sign}(s)$ in the switching control algorithm shown in equation (9) is replaced by the saturation function $\text{sat}(s, \Delta)$, where $\Delta$ is determined by the relay gain $\delta$.

$$ \text{sat}(s, \Delta) = \begin{cases} s & |s| \leq \Delta \\ \text{sign}(s) |s| \leq \Delta \end{cases} \tag{12} $$

The new switching control algorithm is as follows:

$$ u_i = -\Psi_i^T E_{vi} - \delta_i \text{sat}(s_i, \Delta_i) \tag{13} $$

3.2. Sliding mode controller with the compensation of the model

Based on the sliding mode controller mentioned in subsection 3.1, we consider forces and moments of the 2 DOF manipulator $\sigma_M$ in equation (5) in the output of the sliding mode controller, so forces and moments for propellers are as follows and the control block diagram is shown in figure 2.

$$ \tau = u - \sigma_M \tag{14} $$

![Figure 2](image_url)

**Figure 2.** Block diagram of sliding mode controller with the compensation of the manipulator.

4. Simulation

Simulations have been performed to verify the effectiveness of the controller. We use the webots robot simulator to build the UVMS model with hydrodynamics and perform simulations with the proposed control scheme.
4.1. Simulation model
The UVMS designed by lab comprises of a 2 DOF manipulator and a 6 DOF vehicle. The vehicle has eight propellers, so it can be controlled in 6 DOF. The manipulator can move in the xz-plane in the vehicle frame {B}. Main parameters of the real UVMS designed by lab are shown in table 1.

| Parameters of Vehicle | Parameters of link 1 | Parameters of link 2 |
|-----------------------|----------------------|----------------------|
| Mass (m_i)            | 20.14 kg             | Mass (m_2)           | 0.377 kg             |
| Length (L)            | 0.7 m                | Length (L_2)         | 0.2 m                |
| Center of gravity (P_o) | [0, 0, 0.2] m    | Radius (r_2)         | 0.02 m               |
| Moment of inertia (I_1) | diag[0.48, 0.95, 0.55] | Moment of inertia (I_2) | diag[1.3e3, 7.54e5, 1.3e1] |

4.2. Simulation result
As for this UVMS, we get parameters of the sliding mode controller through debugging that are shown in table 2. Those parameters are used for all subsequent simulations.

| Subsystem | \(c_i\) | \(\alpha_{i1}\) | \(\beta_{i1}\) | \(\alpha_{i2}\) | \(\beta_{i2}\) | \(\delta\) | \(1/\Delta\) |
|-----------|---------|-----------------|-----------------|-----------------|-----------------|----------|----------|
| Surge     | 3       | -3              | 5               | -5              | 200             | 5        |          |
| Sway      | 3       | -3              | 5               | -5              | 200             | 5        |          |
| Heave     | 5       | -5              | 15              | -15             | 200             | 5        |          |
| Roll      | 3       | -3              | 10              | -10             | 20              | 1        |          |
| Pitch     | 3       | -3              | 10              | -10             | 20              | 1        |          |
| Yaw       | 3       | -3              | 10              | -10             | 20              | 1        |          |

In simulations, we make the underwater vehicle keep hovering at 5 meters deep and the 2 DOF underwater manipulator controlled by proportional control moves as the figure 3 shows. 10s to 15s, the manipulator lifts half. 20s to 25s, the manipulator extends to horizontal. After 30s, the manipulator restores to vertical.

The results of the sliding mode controller as in equation (11) are shown in figure 4. The controller has a robust effect on the stability of the vehicle. However, because of the change of the center of gravity, there are some errors in surge, heave and pitch channels as shown in figure 4(a), (c) and (e).
Therefore, we add the compensation of forces and moments from the manipulator to the output of sliding mode controller and the simulation results are shown in figure 5. Errors are suppressed significantly. In the pitch channel, compared to the original controller, the error caused by the movement of the manipulator decreases from 0.02 rad to 0.015 rad, which is shown in figure 4(e) and figure 5(e). Figure 4(c) and figure 5(c) show that the deviation of depth is compensated in the heave channel.

To summarize, the compensation of manipulator, as a feed forward, helps the feedback controller to improve system robustness, which enhances the accuracy and stability of the UVMS.

Figure 4. Vehicle states during manipulator motion with sliding mode controller without compensation of manipulator.

Figure 5. Vehicle states during manipulator motion with sliding mode controller with compensation of manipulator.

5. Conclusions
This paper has presented a model reference sliding mode control scheme for UVMS. The compensation for controller is obtained by modelling dynamics of UVMS. Simulation model is built based on the real UVMS and simulations are performed to test the stability. The results indicate that the performance of the proposed control scheme is more accurate and robust than the scheme without compensation. The experiment will be done to verify the effectiveness of the control scheme.
Acknowledgments
The financial supports by Zhejiang Provincial Natural Science Foundation of China (Y18F030012), Qingdao National Laboratory for Marine Science and Technology (2017WHZZB0302), and the State Key Laboratory of Industrial Control Technology, Zhejiang University, China (ICT1807) are acknowledged.

References
[1] Wynn R B, et al 2014 Autonomous underwater vehicles (auvs): their past, present and future contributions to the advancement of marine geoscience Mar. Geol. 352(2) 451–468
[2] Ribas D, Palomeras N, Ridao P, Carreras M and Mallios A 2012 Girona 500 auv: from survey to intervention IEEE/ASME Trans. Mechatronics 17(1) 46–53
[3] Ridao P 2014 Intervention auv: the next challenge World Congr. pp 12146–12159
[4] Fossen T I 1994 Modelling and control of underwater vehicle-manipulator systems Proc.rd Conf.on Marine Craft Maneuvering & Control pp 45–57
[5] Sarkar, N and Podder T K 1999 Motion coordination of underwater vehicle-manipulator systems subject to drag optimization IEEE Int. Conf. Robot. and Autom. vol 1 pp 387–392
[6] Tam T J, Shouls G A and Yang S P 1996 A dynamic model of an underwater vehicle with a robotic manipulator using kane’s method Auton. Robots 3(2-3) 269–283
[7] Fossen T I 1994 Guidance and Control of Ocean Vehicle
[8] McLain T W, Rock S M and Lee M J 1996 Experiments in the coordinated control of an underwater arm/vehicle system Auton. Robots 3(2-3) 213–232
[9] Cui Y, Podder T K and Sarkar N 1999 Impedance control of underwater vehicle-manipulator systems (uvms) IEEE/RSJ Int. Conf. on Intell. Robots Syst. vol 1 pp 148–153
[10] Wang R, Wang S, Wang Y, Tang C and Tan M 2017 Three-dimensional helical path following of an underwater biomimetic vehicle-manipulator system IEEE J. Ocean. Eng. 99 1–11
[11] Wang R, Wang S, Wang Y, Tan M and Yu J 2017 A paradigm for path following control of a ribbon-fin propelled biomimetic underwater vehicle IEEE Trans. Syst., Man, Cybern., Syst. 99 1–12
[12] Olguin-Diaz E, Arechavaleta G, Jarquin G and Parra-Vega V 2013 A passivity-based model-free force–motion control of underwater vehicle-manipulator systems IEEE Trans. Robot. 29(6) 1469–1484
[13] Santhakumar M and J Kim 2011 Modelling, simulation and model reference adaptive control of autonomous underwater vehicle-manipulator systems Int. Conf. Control, Autom., Syst. pp 643–648
[14] Pandian S R, Hayakawa Y, Kamoyama Y and Kawamura S 2002 Practical design of adaptive model-based sliding mode control of pneumatic actuators ieee/asme Int. Conf. on Advanced Intelligent Mechatronics ‘97, Final Program and Abstracts vol 31 p 140
[15] Xu B, Abe S, Sakagami N and Pandian S R 2005 Robust nonlinear controller for underwater vehicle-manipulator systems IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics pp 711–716