Modeling and Depth Control of a Subsurface Robot for Low-Cost Marine Robotics Experiments

Quentin Brateau, Natacha Caouren, Fabrice Le Bars, Luc Jaulin

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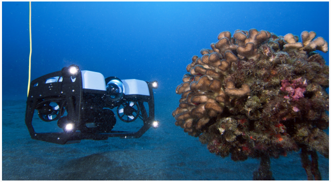
Introduction

Necessity of low-cost marine robots

- Marine robotics is a growing field with applications in environmental monitoring, underwater exploration, and resource management.
- Low-cost solutions are essential for widespread adoption, and swarm experimentation in marine robotics.

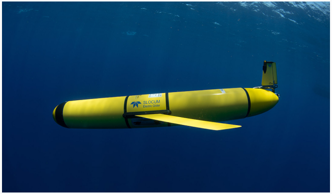
Existing Solutions



(a) BlueROV2 (Blue Robotics)

(b) BlueBoat (Blue Robotics)

(c) Yuco (Seaber)



(d) Slocum (Teledyne Webb Research)

Figure 1: Small marine robots

Main Objective

- Design a subsurface robot low-cost / low-tech
- Use minimal number of actuators and sensors
- Ensure ease of build and maintenance

Benefits

- Low visual, radar, and acoustic signatures
- Reduced drag and improved hydrodynamics
- Enhanced stability and maneuverability

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Modeling

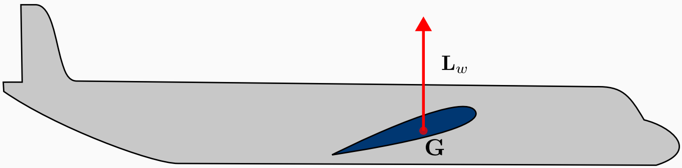

Figure 2: 1 wing plane

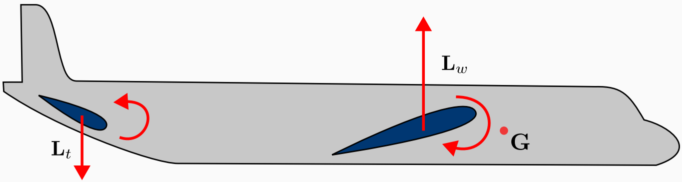

Figure 2: 2 wing plane

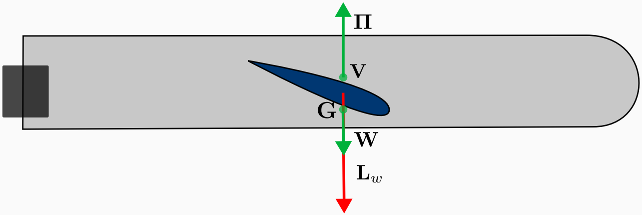

Figure 3: 1 wing subsurface

Forces

- Weight $\mathbf{W} = m\mathbf{g}$
- Buoyancy $\mathbf{\Pi} = -\rho V \mathbf{g}$
- Thrust $\mathbf{F}_x$ from the thruster
- Body Drag $\mathbf{D}_b = \frac{1}{2}\rho C_{D,b} A u|u|$
- Wings Lift $\mathbf{L} = \frac{1}{2}\rho C_L S u|u|$
- Wings Drag $\mathbf{D} = \frac{1}{2}\rho C_D S u|u|$

Equations of motion

$$\begin{cases} m\ddot{x} = F_x - \frac{1}{2}\rho(C_{D,b}A + C_D S)\dot{x}|\dot{x}| \\ m\ddot{z} = (m - \rho V)g + \frac{1}{2}\rho C_L S\dot{x}|\dot{x}| \end{cases} \tag{1}$$

Cruise Speed

$$\dot{x}^* = \sqrt{\frac{2F_x}{\rho(C_{D,b}A + C_D S)}} \tag{2}$$

Equilibrium Vertical Acceleration

$$F_x = \frac{\rho(C_{D,b}A + C_D S)}{2}\sqrt{\frac{2(\rho V - m)g}{\rho C_L S}} \tag{3}$$

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Robot Design

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Material Selection

- PMMA tube for the main body
- 3D-printed parts (FDM / SLA)
- Simple microcontroller (ESP32 / Arduino)

Actuators and Sensors

- Two thrusters for propulsion and steering
- Pressure sensor for depth measurement
- Basic Accelerometer / Gyroscope / Magnetometer (IMU)
- GNSS receiver for surface positioning

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CAD Model

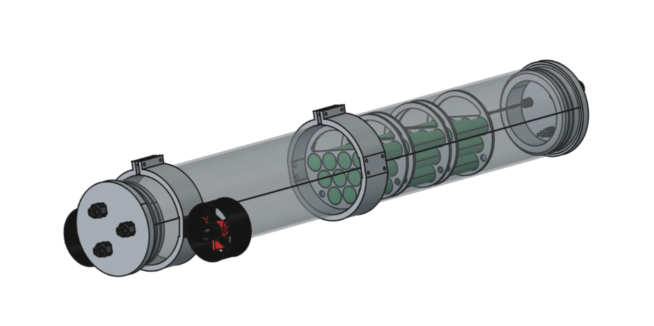

Figure 4: CAD model of the subsurface robot

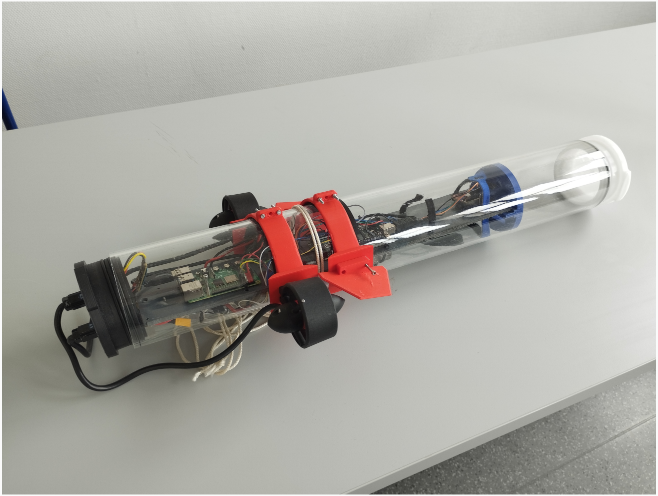

Figure 5: Subsurface robot prototype

Depth Controller

Figure 6: Diagram of the Input / Output relationship for depth control

Dynamical system

$$\dot{\mathbf{x}} = f(\mathbf{x}, t) + g(\mathbf{x}, t)\mathbf{u} \tag{4}$$

Sliding Surface

$$\sigma(\mathbf{x}, t) = \left(\frac{d}{dt} + \lambda\right)^{(n-1)} (\mathbf{x} - \mathbf{x}_d) \tag{5}$$

Sliding Mode Controller

Ensures $\sigma(\mathbf{x}, t) \to 0$

$$\mathbf{u} = \mathbf{u}_{eq} - k\,\mathrm{sign}(\sigma) \tag{6}$$

Dynamical system

$$\dot{\mathbf{x}} = f(\mathbf{x}, t) + g(\mathbf{x}, t)\mathbf{u} \quad (4)$$

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Sliding Surface

$$\sigma(\mathbf{x}, t) = (\dot{z} - \dot{z}_d) + (z - z_d) \quad (7)$$

Finite-time convergence

$$F_x = -sign(\sigma(\mathbf{x}, t)) \quad (8)$$

Asymptotic convergence

$$F_x = -tanh(\sigma(\mathbf{x}, t)) \quad (9)$$

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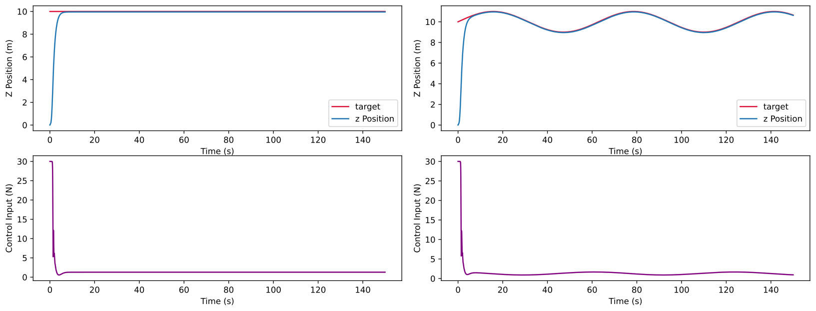

(a) Setpoint

(b) Tracking

Figure 7: Simulation results of SMC depth control

Conclusion

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- Successfully designed a low-cost subsurface robot model
- Developed a sliding mode control strategy for depth regulation
- Simulation results demonstrate effective depth tracking

Future Work

- Build and test the physical robot in real-world conditions
- Implement and validate the control algorithm on hardware
- Test fast navigation strategies

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