Complementary control allocation for a Lagrangian seafloor imaging platform.

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Abstract:
The depth controller for a Lagrangian imaging float is detailed, and performance results from simulation and field experiments are used to demonstrate the utility of a model based controller with a complementary control allocation approach. The float is an over actuated system in depth/altitude, which is the only degree of freedom controlled. Vertical control is accomplished using a combination of active buoyancy modulation and a conventional propeller thruster. The proposed depth control algorithm is designed to take advantage of the high authority, high bandwidth inputs available from the thruster, and the low bandwidth trim input available from the buoyancy controller. The float vertical dynamics are modeled as a double integrator in the input force, and empirically derived parameters are used to simulate actuator inputs and system response over pre-recorded bathymetry profiles. Simulation and preliminary experimental results indicate that significant reductions in actuator power can be achieved in field conditions, and that the combination of thruster and buoyancy control provide the altitude tracking performance required for benthic imaging.

Keywords: Complementary filtering, autonomous vehicles, redundant actuators, depth control.

1. INTRODUCTION

The Shallow Water Lagrangian Float is a man portable underwater vehicle that can be used to generate still imagery of the bottom for tasks such as assessment of ground fish stocks and bottom type classification in coral reefs. The float actively controls its altitude using a piston driven variable displacement system and an external thruster as it drifts laterally with the prevailing current over varying bathymetry [Roman et al. 2011]. The original float design used only the variable displacement system to control its distance from the bottom [Schwithal and Roman 2009]. Although the float was able to capture high resolution bottom images at close range with a down looking camera, the vehicle was prone to depth oscillations around the desired setpoint.

In this paper we present depth control results when a bi-directional vertical thruster is added to complement the auto ballasting system. An image of the float with the thruster mounted external to the main housing is shown in Figure 1. With the thruster installed, the system is over actuated in depth. The present work applies a complementary filter based allocation approach to effectively resolve both low and high frequency disturbances with the appropriate actuator.

The net buoyancy (i.e. the in-water weight) of the vehicle can vary significantly between and during deployments due to variations in water density between deployment locations and throughout the water column. The addition or removal of sensors and other components while at sea often precludes precise ‘trimming’ to initialize the vehicle to neutral buoyancy. The disturbances caused by trim errors are typically constant or slowly changing. The bottom depth, and hence the altitude of the float, may change rapidly. In effect, the complementary allocation approach addresses trim errors with changes in piston volume, while bottom profile following is actuated with the thruster. Simulation and field testing results are presented to demonstrate the effectiveness of the proposed control allocation approach.

2. LINEARIZED DEPTH MODEL

A single degree of freedom model is used to represent the vehicle depth dynamics with the standard first-order simplifying assumption [Fossen 2011] that the fluid forcing can be separated into non-interacting hydrostatic, velocity dependent, and acceleration dependent terms. For the purposes of compensator design, the resulting vehicle depth (z) dynamics were taken to be a double integrator in the vertical force,

\[(m_f + m_a) \ddot{z} = (Z_T - \rho V_p g)\]  \hspace{1cm} (1)

where \(m_f\) is the system mass, \(m_a\) is the fluid ‘added mass’, \(Z_T\) is the thrust from the propeller, and \(V_p\) is the volume of fluid ingested by the internal piston. \(\rho\) and \(g\) are fluid density and gravitational acceleration.
The double integrator results from linearizing about a zero velocity operating point. Fluid forces are assumed to be superposition of quadratic drag (in velocity) and linear pressure force proportional to acceleration (i.e. added mass, $m_a$) with the result that drag can be neglected for an operating point of $z = \dot{z} = 0$.

For the purposes of developing the state feedback controller, the right hand side of (1), which represents the combined effort from piston induced buoyancy changes and the propeller thrust will be defined as the control input

$$u = (Z_T - \rho V_I g) = (Z_T + Z_P).$$

The state space plant model of the vehicle is then

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{1}{m_s + m_a} \end{bmatrix} u,$$
$$y = [1 \ 0] x,$$
$$x = \begin{bmatrix} z \\ \dot{z} \end{bmatrix}. \tag{3}$$

The equivalent discrete model of the simplified depth dynamics for the Lagrangian float can be analytically derived assuming a zero order hold on the control input [Vaccaro 1995]. For a control update period $T$, the equivalent model of the double integrator is as follows,

$$x(k+1) = \Phi x(k) + \Gamma u(k)$$
$$y(k+1) = Cx(k)$$
$$\Phi = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}$$
$$\Gamma = \frac{1}{m_s + m_a} \begin{bmatrix} T^2/2 \\ T \end{bmatrix}$$
$$C = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{4}$$

3. STATE FEEDBACK CONTROLLER

The control allocation algorithm tested here divides the commanded $z$ force between the thruster and piston with-out regard to how the commanded force is derived. As a result the use of a complementary allocation algorithm is not specific to any one feedback control approach.

In [Malerba and Indiveri 2014] a PID depth feedback controller was simulated in combination with a complementary filter based approach for control allocation in a vehicle with four vertical thrusters and active buoyancy control. For this effort, the commanded $z$ force for both simulation and for the fielded system is produced by a state feedback tracking controller following [Vaccaro 1995].

Pole placement is performed for an augmented model which combines the poles of an expected reference trajectory (a step input) with the poles of the plant. This control architecture was originally selected for the Lagrangian float by McGilvray and Roman [2010] in order to meet the system requirement to track sinusoidal and linear depth trajectories. It is retained and adapted here for altitude following by using a step input as the expected reference trajectory.

The augmented model can be written as,

$$\begin{bmatrix} x(k+1) \\ a_x(k+1) \end{bmatrix} = \left[ \begin{array}{cc} \Phi & 0 \\ \Gamma C & \Phi_a \end{array} \right] \begin{bmatrix} x(k) \\ a_x(k) \end{bmatrix} + \begin{bmatrix} \Gamma \\ 0 \end{bmatrix} u(k)$$
$$y(k) = [C \ 0] \begin{bmatrix} x(k) \\ a_x(k) \end{bmatrix} \tag{5}$$

The pole of the step input reference trajectory is included in the augmented dynamic system by defining $\Phi_a$ as an integrator,

$$x_a(k+1) = \Phi_a x(k) + \Gamma_a e(k)$$
$$\Phi_a = 1$$
$$\Gamma_a = 1$$
$$C_a = 1 \tag{6}$$

The augmented system model simplifies to,

$$\begin{bmatrix} x(k+1) \\ a_x(k+1) \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x(k) \\ a_x(k) \end{bmatrix} + \frac{1}{m_s + m_a} \begin{bmatrix} T^2/2 \\ T \end{bmatrix} u[k]$$
$$y(k) = [1 \ 0] \begin{bmatrix} x(k) \\ a_x(k) \end{bmatrix} \tag{7}$$

Pole placement can then be used to choose gain matrices $K_1$ and $K_2$ that produce normalized Bessel poles scaled by a factor $T_s$ using the regulator described by,

$$u(k) = \left[ K_1 K_2 \right] \begin{bmatrix} x(k) \\ a_x(k) \end{bmatrix} \tag{8}$$

The resulting gains used in this effort were,

$$K_1 = [6.3841 \ 41.1525]$$
$$K_2 = [0.0361] \tag{9}$$
4. COMPLEMENTARY CONTROL ALLOCATION

In the present work, we use complementary filters to break down the plant control input into two signals which separately contain the high frequency and low frequency components of the force demand. The thruster responds to the high frequency demand, and the piston responds to the low frequency demand.

For the ideal case where both actuators exactly follow the force demand, the forces would sum to the total plant control input. To approach the ideal, we must design the filters to match the capabilities of the target actuators.

A pair of complementary filters similar to those presented in Malerba and Indiveri [2014] were used. The filter for the thruster was a second order high pass filter described by the transfer function,

$$ Z_T = P_1 = \frac{\tau_f s^2}{\tau_f s^2 + 2\tau_f s + 1}. \quad (10) $$

Where $\tau_f$ controls the cut-off frequency of the filter. The complementary low pass filter for the piston is found using the complementary condition for a sum of $N$ filters

$$ \sum_{k=1}^{N} P_k(s) = 1. \quad (11) $$

This condition requires that the gain of all the filters sum to one across all frequencies. The low pass filter is found to be

$$ Z_P = P_2 = \frac{2\tau_f s + 1}{\tau_f s^2 + 2\tau_f s + 1}. \quad (12) $$

These two filters were implemented in the controller using a zero order hold equivalent discrete filter sampled at the controller’s operating frequency of 10Hz. The operating frequency is limited by the update rate for the altitude measurement, which is performed using an Airmar acoustic altimeter.

5. SIMULATION RESULTS

The behavior of the float was simulated to evaluate the performance of the complementary control allocation algorithm over pre-recorded bathymetry. Three simulation cases are presented.

In Case I, the initial vehicle trim was set to be perfectly neutrally buoyant, i.e. the vehicle’s weight in water was zero, and the thruster alone was used to actuate the vehicle.

In Case II, the initial vehicle trim was set such that the vehicle weight in water was initially 1N, and again the thruster alone was used. Trim errors of this magnitude are consistent with field experience.

In Case III, the initial vehicle trim was again set to 1N, and both the thruster and the piston were used.

The desired trajectory for all three simulations is shown in Figure 2 (top). This trajectory follows actual bathymetry variations experienced by the float during at-sea trials, based on recorded depth and altitude logs from operations at Cordell Bank.

In Cases I & II, the output of the state feedback controller was used directly as the commanded thruster force. In Case III, the output of the same state feedback controller was allocated between thruster and piston demand using the complementary control allocation approach described.

All simulations were performed using realistic sensor inputs, with actuator non-linearities, saturation, and rate limits explicitly modeled. The operation of the controller, the sensor update rates, and all operational parameters were faithful to those of the fielded platform. The use of realistic sensor input and operational parameters was aided by the use of the Light Weight Communication and Marshalling (LCM) software architecture.

Figure 2 shows vehicle depth and bottom depth variation (top) along with power consumption (bottom) for Case II and Case III. In the simulation, bottom following begins at time $t = 5$ minutes, and continues until the end of the simulation at $t = 50$ minutes for a total bottom time of 55 minutes. Error and power consumption for each case are given in Table 1. The effect of combining piston and thruster is clearly evident in the power consumption. Using the thruster only controller, the mean power consumption is 6.03 W. Using complementary control allocation to combine thruster and piston effort, the mean power consumption is 3.23 W, a 47% reduction. In Case I, the ideal but physically unrealistic scenario in which the vehicle weight in water is exactly zero, the power consumption is 2.5 W.

In the thruster only approach, thruster power is modulated around a mean power draw of nearly 6 W, which represents the thruster power required to counteract the constant disturbance caused by the weight of the vehicle. When the piston is included using the complementary approach, the mean power draw for the thruster drops as the piston volume changes to compensate for the trim error.

The power spikes in the complementary approach are associated with changes in the piston volume. The piston moves in discrete, constant velocity steps whenever the piston control demand exceeds a threshold value. As a result, the piston power consumption is modeled such that:

$$ P_P = \begin{cases} \mu_{\text{in}}, & V_P \geq 0 \\ 0, & V_P = 0 \\ \mu_{\text{out}} + \rho g A_P V_P, & V_P \geq 0 \end{cases} \quad (13) $$

$\mu_{\text{in}}, \mu_{\text{out}}, A_P,$ and $|V_P|$ are constant values representing observed power during piston contraction, observed power constant during piston extension, piston area, and piston linear velocity, respectively. When the piston is not moving, the power consumption is zero, since it is not back drivable. When the piston volume is increasing, power is required to overcome internal resistance and the hydrostatic pressure opposing the motion on the piston head. The hydrostatic pressure is proportional to depth, thus the piston power linearly increases with increasing depth.

When the piston volume is decreasing, power is modeled
as the power required to overcome the internal mechanical resistance. The effect of hydrostatic pressure is negligible because the gearing is not back drivable. At a depth of approximately 50 meters the piston draws approximately 30 W when the volume is increasing. Note that the peak power draw in Case III is thus significantly higher than in Case II, despite the reduction in the mean power consumption.

In all cases studied, use of the complementary allocation algorithm to add piston actuation has a negligible impact on the tracking performance. In Case II, the root mean square (RMS) error for the thruster only control approach is 0.395m, while in Case III the RMS error for the complementary control approach is 0.391, a 1% reduction. The vehicle depth dynamics are independent of the depth and altitude, and the differences in tracking performance in Case I and Case II was likewise negligible.

### 6. FIELD TEST RESULTS

The complementary control approach was implemented during float deployments from the R/V Falkor at Scott Reef in the Sea of Timor. The float was deployed for 21 dives between March 26th and April 4th. The primary objective was to obtain sea floor imagery from altitudes between 2 and 3 meters. Of the 21 dives, 11 were conducted with the float tethered to a surface buoy, and 10 were conducted without a tether or buoy.

To begin each dive, the float is instructed to descend to a depth within 30m of the seafloor. The float holds depth until range to the seafloor is acquired by the acoustic altimeter. The float then proceeds to the commanded altitude, enables the cameras, and begins acquiring images at regular time intervals while maintaining altitude.

Figure 3 shows an example of this behavior during an untethered dive at Scott Reef, along with the desired allocation of the depth control input between thruster and piston. During this dive, the controller used the piston and thruster in concert to rapidly descend to the bottom. Once the bottom was reached, the piston slowly settled to a nearly constant value. The thruster effectively compensates for the net negative buoyancy up until the point at which the piston settles to a volume resulting in near neutral buoyancy. Once the piston volume settled, the thruster force was centered around zero throughout the rest of the dive bottom time. The steady state piston position that results implies a 1.9N negative vehicle trim at nominal zero piston volume. The piston command settled over approximately seven minutes, consistent with the 400 second settling time of the low pass filter.

The sensitivity of the control allocation approach to the time constant, \( \tau_f \), is illustrated using results from three field trials for each of two values of \( \tau_f \). Results from sixty minutes of bottom time from three representative untethered dives with a complementary filter time constant \( \tau_f = 400s \) are presented in Figure 4. As shown in Figure 4 (top), the within-dive depth variation ranged from 4m to 9m. Piston volumes are plotted in Figure 4 (middle) as differences from a starting value recorded well after the controller has transitioned from descent mode to bottom following mode. The recorded change in piston volume is less 10ml for all dives. Piston volume changes only occur when a 2ml error threshold is exceeded. The thruster current is shown in Figure 4 (bottom). When the magnitude of the demanded thruster current drops below a cut-in value, it is set to zero.

The thruster current is centered about zero throughout all dives, while the piston makes small changes on average every 4.4 minutes across all dives shown. Based on these results it is reasonable to infer that the piston has driven the net buoyancy to within 0.1 N of net zero. With near zero buoyancy, the thruster successfully tracks the changes in bottom topography with a mean RMS error of less than 0.27m in all cases. Near zero buoyancy coupled with minimal piston moves results in a power usage of 0.70W in the worst case and 0.41W and 0.40W in the other two dives.

Figure 5 shows the results for three untethered dives with \( \tau_f = 200s \). Scaling is preserved for direct comparison to
results with \( \tau_f = 400s \). The bottom topography encountered is similar, but not identical to the previous cases. The most significant difference is in the power consumption. Average power consumption is 2.8 times higher for the active throughout, and as a result the piston consumes a higher fraction of the total power. For \( \tau_f = 400s \) the piston consumes between 2.5% and 7.1% of the propulsion power. For \( \tau_f = 200s \) the piston consumes between 24% and 42% of the propulsion power. This is consistent with expectations, as lowering the time constant has the effect of reallocating control responsibilities from the thruster to the piston. The average tracking performance is degraded by 15% at the lower time constant.

7. CONCLUSION

The simulation and preliminary field testing results presented indicate that complementary filtering of the depth input for an over-actuated vehicle can be used to allocate control between actuators with very different capabilities. The primary advantage of the proposed method over heuristic approaches to control allocation is the introduction of a physically meaningfully parameter, \( \tau_f \), into the tuning process. The parameter \( \tau_f \) is best interpreted as a time constant corresponding to the bandwidth at which primary responsibility for disturbance rejection is shifted between the low bandwidth and high bandwidth actuators. 

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