Ocean Engineering 127 (2016) 305–324

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Station-keeping control of an unmanned surface vehicle exposed to current and wind disturbances

Edoardo I. Sarda*, Huajin Qu, Ivan R. Bertaska, Karl D. von Ellenrieder

Florida Atlantic University, SeaTech - The Institute for Ocean and Systems Engineering, 101 N Beach Rd, Dania Beach, FL 33004, USA

A R T I C L E I N F O

Keywords:
Station-keeping
Nonlinear control
Wind feedforward
Unmanned surface vehicles

A B S T R A C T

Field trials of a 4 m long, 180 kg, unmanned surface vehicle (USV) have been conducted to evaluate the performance of station-keeping heading and position controllers in an outdoor marine environment disturbed by wind and current. The USV has a twin hull configuration and a custom-designed propulsion system, which consists of two azimuthing thrusters, one for each hull. Nonlinear proportional derivative, backstepping and sliding mode feedback controllers were tested in winds of about 4–5 knots, with and without wind feedforward control. The controllers were tested when the longitudinal axis of the USV was aligned with the mean wind direction and when the longitudinal axis was perpendicular to the mean wind direction. It was found that the sliding mode controller performed best overall and that the addition of wind feedforward control did not significantly improve its effectiveness. However, wind feedforward control did substantially improve the performance of the proportional derivative and backstepping controllers when the mean wind direction was perpendicular to the longitudinal axis of the USV. An analysis of the length scales present in the power spectrum of the turbulent speed fluctuations in the wind suggests that a single anemometer is sufficient to characterize the speed and direction of the wind acting on the USV.

1. Introduction

Unmanned Surface Vehicles (USVs) are playing increasing roles in commercial, scientific and military applications (Manley, 2008). Once equipped with advanced control systems, sensor systems, communication systems and weapon systems, they can perform a variety of missions that include sea patrol, environmental monitoring, pollutant tracking, surveillance, underwater terrain mapping and oceanographic research (Bertaska et al., 2013, 2015; Kitts et al., 2012; Murphy et al., 2011; Sarda et al., 2014; Busquets et al., 2012; Casalino et al., 2009). To be effective, a USV needs to be capable of autonomously performing a variety of distinct maneuvers, with trajectory tracking and station-keeping being essential in their roles. While the former is necessary to allow the vehicle to navigate within different locations, the latter allows the system to maintain constant position and heading over a period of time. A potential application of USVs is the automatic launch and recovery (ALR) of smaller unmanned systems, such as autonomous underwater vehicles (AUVs) (Sarda et al., 2014; Klinger et al., 2013; Pearson et al., 2014) and object localization using acoustic (Miranda et al., 2013) or vision subsystems (Huntsberger et al., 2011; Kuwata et al., 2014; Lebbad and Nataraj, 2015). Underwater object localization via acoustics can require maintaining a fixed position and orientation for up to one minute, allowing the filters in the acoustic system to remove refraction noise, thereby improving measurement accuracy (Miranda et al., 2013). The performance of the acoustic sensors can be heavily affected if the vehicle drifts during the measurement. A similar case is that of optical localization using a camera. Here, image processing algorithms may require a few seconds; however, the performance is heavily affected if the vehicle's heading is not maintained constant, since small motions of the camera may result in dramatic changes in lighting conditions and image perspective. The ALR of an AUV from a USV is a complex task that requires precise collaboration between the USV on the surface and the AUV underwater. The process can be simplified by fixing the USV position on the surface to reduce the number of moving objects, so that the problem is essentially transformed to the static docking of the AUV (Sarda and Dhanak, 2013). Thus, enabling a USV to station-keep can convert complicated tasks into simpler ones.

Since the present generation of USVs are lightweight and have relatively large windage areas, wind is a major source of disturbance during station-keeping operations (Schlipf et al., 2012). While slowly varying environmental changes, such as tidal currents, can be attenuated by applying robust feedback control laws, rapid environmental changes, like the ones caused by wind, can be better counteracted by

* Corresponding author.
E-mail address: esarda@fau.edu (E.I. Sarda).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.037
Received 24 October 2015; Received in revised form 20 September 2016; Accepted 24 September 2016

applying feedforward control theory (Kitamura et al., 1997). This research highlights that the uncertain effect of currents on a small twin-hulled USV, tasked to autonomously station-keep, leads to the inability of the system to reach and maintain the desired state. It is shown that robust non-linear control theory, such as backstepping and sliding mode control, can be applied and refined for the purpose of heading and position station-keeping of a USV. It is also shown that, implementing wind feedforward control, in addition to state feedback control, allows for fast correction of the final control signal, therefore providing the appropriate control effort.

Different options for the station-keeping control of a small twin-hulled USV are presented. More precisely, three station-keeping controllers are designed and implemented on a USV: a Proportional Derivative (PD) nonlinear controller, a Backstepping Multiple Input Multiple Output (MIMO) PD nonlinear controller and a Sliding Mode MIMO nonlinear controller. A wind feedforward control feature was also designed and added to the system to assist each station-keeping feedback controller. Experimental on-water station-keeping test results are presented for all three controllers, implemented with and without the wind feedforward feature. The outcomes of this work are the development and experimental validation of an optimal station-keeping control system for a USV tasked with common objectives, such as ALR and object localization.

Here, the performance of the controllers developed in Sarda et al. (2015) and Qu et al. (2015) is improved by using a revised and validated dynamic model for the USV16. Previously, a model of a WAM-V USV14 (Marquardt et al., 2014) had been adapted for the development of a station-keeping controller by simply scaling the physical parameters in the model to those of the USV16 (shown in Table 1 below). Apart from the propulsion system, the WAM-V USV16 is essentially a scaled version of the WAM-V USV14. This had been found to be acceptable for initial trials. However, for this effort, a more accurate model is developed for the WAM-V USV16 using the procedure outlined in Marquardt et al. (2014), and through additional on-water experimentation it is found that the performance of the controllers is improved.

This paper is organized as follows. Recent advances in station-keeping control and wind feedforward control for USVs are presented in Section 2. The principal characteristics of the vehicle used in this research are described in Section 3, with emphasis on the propulsion system. In Section 4, the development of a control oriented state space model of the vehicle and the wind is described. Three alternatives for station-keeping control and one option for wind feedforward control are explored in Section 5. The Lagrangian multiplier method with an extended thrust representation used for control allocation is explained in Section 6. In Section 7, the controllers' station-keeping performance with and without the aid of the wind feedforward controller is compared. Finally, in Section 8, some concluding remarks are given regarding the results shown and possible future work.

2. Literature review

Nonlinear control of USVs is currently an active area of research, with the majority of the effort devoted towards feedback linearization and backstepping methods (Liao et al., 2010; Fossen and Strand, 1999; Ashrafiuon et al., 2013; Sonnenburg et al., 2013; Aguiar and Hespanha, 2003; Do, 2010; Mahini and Ashrafiuon, 2012), as well as sliding mode control (Alvarez et al., 2013; Ashrafiuon et al., 2013; Mahini and Ashrafiuon, 2012). However, the validation of USV control laws is often limited to numerical simulation or small-scale experiments, rather than full-scale sea trials (Ashrafiuon et al., 2010). In fact, even in more technologically mature areas such as AUV control, stabilization in the presence of environmental disturbances has only been partially addressed (Aguiar and Pascoal, 2007). Several solutions have been proposed for the station-keeping of surface vehicles. In Pereira et al. (2008), experiments were performed on a small underactuated USV with high windage, where a feedforward wind model was modified to accommodate a PD-based heading autopilot. In Chen et al. (2013), the feasibility of reducing USV drift rate, considering the wave drifting effect as the vehicle is under station-keeping mode, is discussed. Elkaim and Kelbley (2006) were able to add station-keeping functionality to a wind propelled autonomous catamaran for the purpose of maintaining position at a given waypoint in the presence of unknown water currents. Switching between point and orientation stabilization and discontinuous control was employed to stabilize a marine vehicle at a fixed point in the presence of a current using dipolar vector fields as guidance in Panagou and Kyriakopoulos (2011, 2014). Similarly, a hybrid approach was taken in Nguyen et al. (2007) where multi-output PID controllers with and without acceleration feedback were used to stabilize a vehicle in high sea states by the use of an observer to estimate the peak wave frequency. The system switched to controllers better suited to handle large disturbances as the peak wave frequency estimate decreased and, correspondingly, the sea state increased. Aguiar and Pascoal (2007) devised a nonlinear adaptive controller capable of station-keeping an AUV with uncertain hydrodynamic parameters in the presence of an unknown current. Backstepping also was suggested in Fossen et al. (2006) as means to station-keep a fully-actuated vehicle, although environmental disturbances were not explicitly stated in the problem formulation. Most previous work on USV station-keeping control focuses on underactuated systems and on enabling the vehicle to maintain position only, as if it was anchored, and without focusing on the USV orientation. Here we describe the development of an ideal station-keeping controller for an overactuated USV, enabling it to simultaneously maintain heading and position.

The USV application of feedforward control theory, such as wind feedforward control, still has not been widely explored. A few challenges are encountered when designing wind feedforward controllers. These include accurately measuring representative wind speed and direction and calculating the wind force coefficients. Anemometer errors can be minimized, but not eliminated, by appropriately calibrating the sensor (Kitamura et al., 1997). It has been found that wind gust and turbulence can also cause large measurement errors (Schlipf et al., 2012). A risk of applying wind feedforward control is that the speed and direction of the wind can vary across different parts of a vessel. Thus, especially for larger vehicles, it may not be appropriate to analyze wind effects on the whole vessel with a single point measurement. One possible solution is to use several wind anemometers to measure the wind field (Schlipf et al., 2012). For small USVs, the wind acting on the vehicle can be assumed to be uniform. The placement of the anemometer on the vehicle presents another challenge. Ideally, it should be mounted such that the measurements are least affected by wind interaction with the vehicle's structure. Lastly, wind models, capable of estimating wind forces and moments acting on small marine vessels,

Table 1
Principle characteristics of the WAM-V USV16. The location of the "keel" is taken as the bottom of the pontoons. w.r.t. is an acronym for the phrase "with respect to".

Parameter	Value
Length overall (L)	4.05 [m]
Length on the waterline (LWL)	3.20 [m]
Draft (aft and mid-length)	0.30 and 0.23 [m]
Beam overall (BOA)	2.44 [m]
Beam on the waterline (BWL)	2.39 [m]
Depth (keel to pontoon skid top)	0.43 [m]
Area of the waterplane (AWP)	1.6 [m^2]
Centerline-to-centerline side hull separation (B)	1.83 [m]
Length to beam ratio (L/B)	2.0
Volumetric displacement (∇)	0.5 [m^3]
Mass	180 [kg]
Mass moment of inertia about z axis (estimated with CAD)	250 [kg-m^2]
Longitudinal center of gravity (LCG) w.r.t. aft plane of engine pods	1.30 [m]