Trajectory Controller for Autonomous Surface Vehicle Under Sea Waves

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***Abstract*—This paper presents a solution to the trajectory-tracking control problem of an Autonomous Surface Vehicle (ASV) under the effect of sea waves. Worldwide, there has been increasing interest in the use of ASVs to execute missions of increasing complexity without direct supervision of human operators. A key-enabling element for the execution of such missions is the availability of advanced systems for motion control of ASVs. The problems of motion control can be roughly classified into three groups: i) point stabilization, where the goal is to stabilize a vehicle at a given target point with a desired orientation; ii) trajectory tracking, where the vehicle is required to track a time parameterized reference; and iii) path following, where the objective is for the vehicle to converge to and follow a desired geometric path, without an explicit timing law assigned to it. In some applications where it is critical for ASVs to follow the preplanning trajectory as closely as possible, the trajectory problem of ASVs becomes important.**

Keywords*—*ASV; Sea waves; Motion control;

I. Introduction

This paper addresses the trajectory-tracking control problem of an Autonomous Surface Vehicle (ASV) (see Fig. 1) under the effect of sea waves, taking explicitly into account the physical limitations of the vehicles. Worldwide, there has been growing interest in the use of ASVs to execute missions of increasing complexity without direct supervision of human operators. A key enabling element for the execution of such missions is the availability of advanced systems for motion control of ASVs. The problems of motion control can be roughly classified into three groups: i) point stabilization, where the goal is to stabilize a vehicle at a given target point with a desired orientation; ii) trajectory tracking, where the vehicle is required to track a time parameterized reference; and iii) path following, where the objective is for the vehicle to converge to and follow a desired geometric path, without an explicit timing law assigned to it. In some applications it is critical for ASVs to follow the preplanning trajectory as closely as possible. For example, during optical communication with an Autonomous Underwater Vehicle (AUV), the ASV must "hover" above the AUV. AUVs operate in unknown underwater environments and must make decisions based on sensor readings. Additionally, it is critical for the AUVs to be able to transmit recording data to the operator in real time to make critical decisions [1, 2].

Current research done in this area deals mainly with ocean currents [3, 4], and rudder dumping against rolling and pitching motion [5]. The controller allows the vehicle to perform trajectory-tracking under the effect of sea waves. The coupling between attitude and position makes the trajectory tracking control problem, in particular, hard especially because of the sea waves. In order to solve the trajectory control problem under the effect of sea waves two simple controllers were employed. The first controller focuses on achieving attitude regulation while the second performs trajectory tracking. Then, the sum of two independent controllers is used as input to the rudder angle of the ASV.

Fig. 1 Autonomous Surface Vehicle in Red Sea, Eilat.

II. Platform

The ASV was developed at the Laboratory of Autonomous Robotics (LAR) in Ben-Gurion University of the Negev Department of Electrical and Computer Engineering in order to increase the operational capability of AUVs by cooperation [6-9]. An off-the-shelf 4-meter long kayak manufactured by Ocean Kayak was employed to implement the ASV (Fig. 1). ASVs can be deployed with various kinds of payload sensors for specific experimental needs. The control boards and necessary software were developed at LAR.

A thruster produced by Torqeedo [10] is used for the propulsion while a steering servo is employed for steering of the ASV. The main vehicle computer is an ARM microcontroller. The controller is responsible for trajectory tracking and communication with the base/command station.

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The MAVLINK protocol was used here [11]. Communication and control are possible with a remote controller radio and receive pair MHX2420 by Microhard systems. The Global Positioning System (GPS) u-blox NEO-7, compass HMC5883L, and Inertial Measuring Unit (IMU) AP-6110LR are directly connected to an additional microcontroller, allowing position and attitude estimation in real time.

III. Modeling

In this section, the dynamic equations of the ASV's motion are outlined. The ASV has one hull with one thruster, while for changing heading a steering servo is employed. In general, any movement of a vehicle in a 3D space involves six DOFs. It is convenient to define two coordinate frames, as shown in Fig. 2.

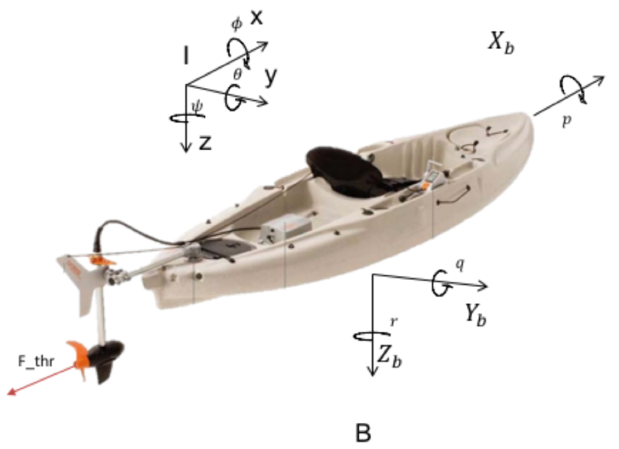

Fig. 2 The ASV body frame and the motor thrust forces.

A. Kayak Model

The body frame mechanical system motion is given by (1).

$$m\dot{v_b} + \omega_b \times m v_b = F_b$$
$$J\dot{\omega_b} + \omega_b \times J\omega_b = M_b \tag{1}$$

where J is the inertia tensor with respect to the body frame, ω_b is rotation velocity, v_b is linear velocity, and F_b and M_b are forces and moment with respect to the body frame, respectively.

The above equations describe how the forces and moments affect the translational and rotational velocity of the rigid body. The kinematic equations that allow relating quantities defined in terms of the body coordinate system to quantities in the inertial system, and vice versa, must be stated. Roll, pitch, and yaw are the rotations of the body about the x, y, and z axes, respectively. The transformation R_i^b (described in (2)) was calculated by cascading the 3 separate angular transformation matrices. The order of the rotations from the inertial frame of reference was: rotation about the z-axis with the yaw angle ψ, then rotation about the y-axis with the pitch angle θ, and, finally, rotation about the x-axis with the roll angle ϕ. The following coordinate transform relates a vector in body-fixed coordinates with a vector in inertial or earth-fixed coordinates [12].

$$R_i^b = \begin{bmatrix} c\theta c\psi & c\psi s\theta s\phi - c\phi s\psi & c\psi s\theta c\phi + s\phi s\psi \\ c\theta s\psi & c\phi c\psi + s\theta s\phi s\psi & -s\phi c\psi + s\theta c\phi s\psi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \tag{2}$$

where $s\alpha \doteq \sin\alpha$ and $c\alpha \doteq \cos\alpha$.

Let the Euler angles vector be $\zeta \doteq [\phi, \theta, \psi]^T$, the rotation speed vector be $\omega_b \doteq [p, q, r]^T$, and the linear velocity in body axes be $v_b = [u, v, w]^T$. We wish to express the relationship between the body angular velocity ω_b and the Euler vector rate of change $\dot{\zeta} = [\dot{\phi}, \dot{\theta}, \dot{\psi}]^T$. Assuming that $\theta \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, (3) is obtained, and since $\det L_{ib} = 1/\cos\theta$ is the relationship between the angular velocity and the Euler angle, rates may be inverted provided that $\theta \neq \pi/2$. Assuming that this is the case,

$$\dot{\zeta} = L_{ib}(\zeta)\omega_b \tag{3}$$

where

$$L_{ib} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \tag{4}$$

As the vehicle motion does not normally approach the singularity condition this is not a serious constraint. If this situation occurs, then it would become necessary to model the vehicle motion using extreme pitch angles, and the analysis could then resort to an alternative kinematics representation, such as quaternions.

Applying (1) and (3), the motion of the vehicle is described by (5).

$$\dot{v_b} = -\omega_b \times v_b + \frac{F_b}{m}$$
$$\dot{\zeta} = L(\zeta)\omega_b$$
$$\dot{\omega_b} = -J^{-1}\omega_b \times J\omega_b + J^{-1}M_b \tag{5}$$

Since the water vehicle is considered a rigid body, the force F_b and the moment M_b are due to the action of the hydrodynamic, propulsive, gravitational, wave, and buoyancy field forces. The result of the combined external forces and moments is described as follows [13]:

$$F_b = [\vec{F}_{bodydrag} + \vec{F}_{thrust} + \vec{F}_{waves}]$$
$$M_b = [\vec{M}_{bodydr} + \vec{M}_{thrust} + \vec{M}_{waves}] \tag{6}$$

In what follows, the cross product for $c, d \in R^3$ is expressed as a matrix operator, that is $S(c)d = c \times d = -d \times c$, where $S(\cdot)$ is a 3×3 skew symmetric matrix. Applying the rotation matrix R_i^b in (2), the following state-space model of the considering system is obtained:

$$\dot{\chi_1} = \chi_2$$
$$\dot{\chi_2} = \frac{R_b^i(\zeta)F_b}{m}$$
$$\dot{\zeta} = L_{ib}(\zeta)\omega_b$$
$$\dot{\omega_b} = J^{-1}S(J\omega_b)\omega_B + J^{-1}M_b \tag{7}$$

where $\chi_1 = [x, y, z]^T$ is the position vector of the vehicle center of mass in terms of the inertial frame, $\chi_2 = [\dot{x}, \dot{y}, \dot{z}]^T$.

B. Rudder Model

The thrust from the propeller can be directed at various orientations on rudder angle α_r, because the vehicle has a vectored thruster. Therefore, depending on the orientation of the thruster (see Fig. 3), the applied force in the body–referenced frame is:

$$F_{thrust} = [F * \cos(\alpha_r), F * \sin(\alpha_r), 0] \tag{8}$$

Since this force may not be coincident with the body axis, a moment is induced in the pitch and yaw directions due to the thrust.

$$M_{thrust} = \begin{bmatrix} x_p \\ 0 \\ 0 \end{bmatrix} \times F_{thrust} = [0, 0, x_p F * \sin(\alpha_r)] \tag{9}$$

where x_p are the distances from the motors to the body center of mass, and α_r is the angle of rudder, with regard to the thrust produced by the thruster and change angle of the thruster for change the heading. The force and moment of thrust in (6) are given by (8) and (9).

Fig. 3 The ASV rudder system.

C. Wave model

A marine control system can be simulated under the influence of wave-induced forces by separating the 1st order and 2nd order effects [14, 15], where 1st order is wave frequency motion and 2nd order is wave drift forces. The approximation of wave transfer function can be written as the following:

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{10}$$

In this research the linear state-space models method was used. This method is frequently used due to its simplicity but it is only intended for testing of robustness and performance of control systems [16]. The model diagram is presented in Fig. 4.

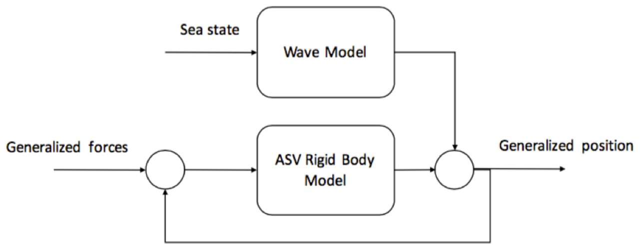

Fig. 4 ASV model with sea waves.

IV. STABILIZING CONTROLLER FOR THE ATTITUDE SUBSYSTEM

A. Heading regulation

In the controller design it is assumed that all state variables are measured. It is important to state that both the ζ and ω_b subsystems in (7) are independent of the position and velocity vectors χ_1, χ_2, respectively, while the attitude ζ vectors are highly coupled with the vector ω_b.

We concentrate now on the attitude subsystem, defined by:

$$\begin{aligned} \dot{\zeta} &= L_{ib}(\zeta)\omega_b \\ \dot{\omega}_b &= J^{-1}S(J\omega_b)\omega_B + J^{-1}M_b \end{aligned} \tag{11}$$

Following the approach and results in [17] the following attitude controller is defined:

$$M_{thrust} = -\left(L_{ib}(\zeta)K\zeta + B\omega_b + \vec{M}_{bodydr} + \vec{M}_{waves}\right) \tag{12}$$

where $K = K^T, B = B^T > 0$ are arbitrarily selected constant matrices. Using (11) and the Lyapunov condition, the stability of the system can be proved.

$$V(\zeta, \omega_b) = \frac{1}{2}[\zeta^T K \zeta + \omega_b^T J \omega_b] \tag{13}$$

Substituting M_{thrust} (12) into (11), the derivative of V along the trajectories of the resulting closed-loop system, namely $\dot{V} = \zeta^T K \dot{\zeta} + \omega_b^T J \dot{\omega}_b$, satisfies:

$$\begin{aligned} \dot{V} &= \zeta^T K L_{ib}(\zeta)\omega_b + \omega_b^T S(J\omega_b)\omega_B \\ &+ w_b^T\left(\vec{M}_{bodydr} + \vec{M}_{thrust} + \vec{M}_{waves}\right) \end{aligned} \tag{14}$$

When $S(J\omega_b)$ is skew symmetric, then $\omega_b^T S(J\omega_b)\omega_B = 0$ and $\zeta^T K L_{ib}(\zeta)\omega_b = \omega_b^T L_{ib}^T K \omega_B$. Therefore (14) can be written as:

$$\begin{aligned} \dot{V} &= \zeta^T K L_{ib}(\zeta)\omega_b + \omega_b^T\left(\vec{M}_{bodydr} + \vec{M}_{ARM}\right) \\ &- \omega_b^T\left(L_{ib}(\zeta)K\zeta + B\omega_b + \vec{M}_{bodydr} + \vec{M}_{EST}\right) \\ &= -\omega_b^T B \omega_b - (\vec{M}_{EST} - \vec{M}_{ARM}) \end{aligned} \tag{15}$$

where $\vec{M}_{EST}$ is the estimated moment that guarantees system stability. The subsystem will be stable if $\dot{V} < 0$; then we can choose $\vec{M}_{EST} > Maximum\ \vec{M}_{waves}$. Since the moments of the waves are limited, the stability is guaranteed.

B. Position regulation

Due to the non-linear coupling between the attitude and the position variables, the process of attitude regulation is associated with drift in the $\chi_1 = [x, y, z]^T$ coordinates. To reduce the resulting drift, an additional non-linear controller for position regulation is proposed.

The position subsystem is defined by:

$$\begin{aligned} \dot{\chi}_1 &= \chi_2 \\ \dot{\chi}_2 &= \frac{R_b^i(\zeta)F_b}{m} \end{aligned} \tag{16}$$

In order to stabilize the position subsystem, F_{thrus} is defined as:

$$F_{thrust} = [-F_{bodydr} - F_{EST} - R_i^b(\zeta)^{-1}(\chi_1 m + \chi_2)] \tag{17}$$

where $A = A^T > 0$ are arbitrarily selected constant matrices. If $\det\left(R_i^b(\zeta)\right) = 1$ for all θ *and* ψ, then $R_i^b(\zeta)^{-1}$ will always exist. Using the Lyapunov stability condition the stability of the system can be probed. The following Lyapunov function is proposed:

$$V_2 = \frac{1}{2}(\chi_1^T A \chi_2 + \chi_2^T A \chi_2) \tag{18}$$

Substituting F_{thrust} from (17) into (16), the derivative of V_2 along the trajectories of the resulting closed-loop system, namely $\dot{V}_2 = \chi_1^T A \dot{\chi}_1 + \chi_2^T A \dot{\chi}_2$, satisfies:

$$\dot{V}_2 = \chi_1^T A \chi_2 + \frac{\chi_2^T A R_i^b(\zeta) F_b}{m} = \chi_1^T A \chi_2 + \frac{\chi_2^T A(-\chi_1 m - \chi_2)}{m}$$
$$= -\chi_2^T A \chi_2 - (F_{EST} + F_{waves})$$

where $\vec{F}_{EST}$ is the estimated force that guarantees system stability and F_{waves} is the waves' force. The subsystem is stable if $\dot{V} < 0$; then we can choose $\vec{F}_{EST} > Maximum\ \vec{F}_{waves}$.

V. RESULTS

A. Simulation Result

This example demonstrates the action of the two controllers (attitude and position). The considered initial condition is $\zeta(0) = \left[0,0,\frac{\pi}{18}\right]^T$ (angles in radians) and the initial position is $\chi_1 = [0,10,0]$. The attitude non-linear controller tries to achieve zero attitude and position on the y-axis. The non-linear controller's objective is to keep the ASV in its trajectory. The results of both controllers are shown in Fig. 5. The red line on the top graph represents the target trajectory while the blue line shows the actual position of the ASV. On the bottom graph the blue line represents the heading position while the desired position is zero degrees.

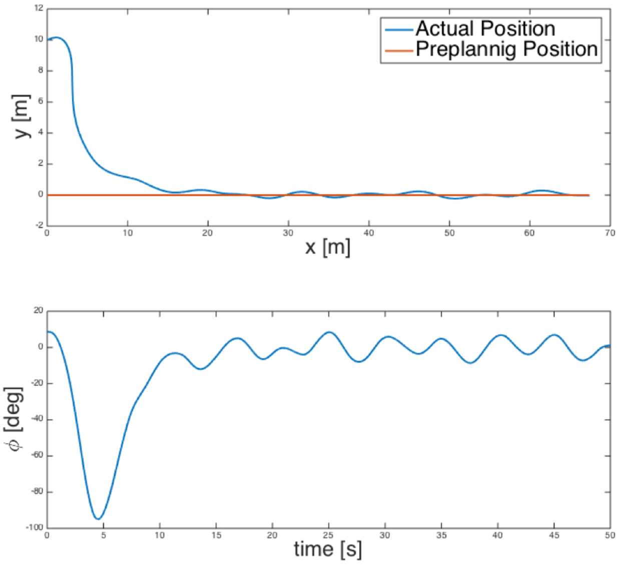

Fig. 5 Trajectory controller performance results.

Most errors from the desired trajectory are less than half a meter (Fig. 6). Larger errors were obtained because the initial state was ten meters from the preplanning trajectory, as can be observed from Fig. 5.

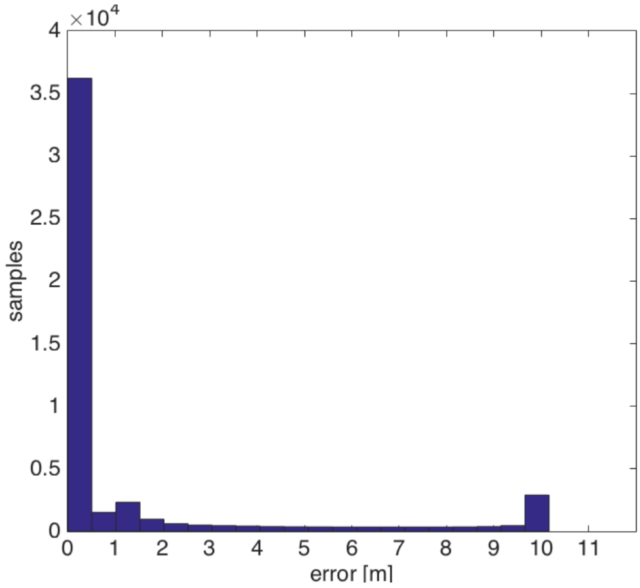

Fig. 6 Histogram of error.

B. Preliminary Experimental Result

The trajectory-tracking controller was implemented on the presented ASV. The experiments took place in the Israeli coast of the Mediterranean Sea. On the experiment day wave height and frequency were about 80 cm and 0.5 Hz, respectively. The experimental results of both controllers are shown in Fig. 7. The red line represents the target trajectory while blue line shows the actual position of the ASV.

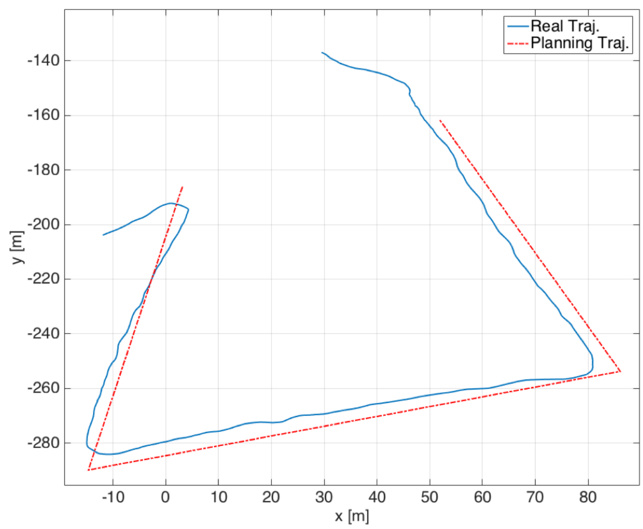

Fig. 7 Trajectory controller performance experemental results.

VI. CONCLUSIONS

The main goal of this research was to develop non-linear controllers for stabilizing the ASV while following the pre-planning trajectory under sea waves. A relatively simple controller for regulating the attitude and position subsystems for the highly non-linear ASV system has been presented.

The paper proposes a trajectory-tracking controller based on two controllers, one for heading and the second for position. Stability analysis of the controllers was also presented.

Simulation and experimental results demonstrate the controller performance.

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