Shared Control of Unmanned Surface Vehicles

Karl von Ellenrieder[*†], Senior Member, IEEE, Jared Wampler[*], Travis Mosciki[*] and Roberto Belotti[†]
[*]Department of Ocean & Mechanical Engineering, Florida Atlantic University, Dania Beach, USA
[†]Facoltà di Scienze e Tecnologie, Libera Università di Bolzano, Bolzano, Italy
Email: [†]kvonellenrieder@unibz.it, [*]ellenrie@fau.edu

Shared human-robot control for the trajectory tracking of a USV is explored. Such a system could be useful for assisting human supervisors of human-USV teams to oversee the transiting of USVs through congested port environments. In this scenario, an automatic trajectory planner computes a desired trajectory minimizing the cost to transit, reducing mission risks, or avoiding obstacles the human supervisor cannot see. The human can alter the trajectory with a force-feedback controller. The shared controller pushes back against the user's hand to keep the vessel on the planned trajectory when deviations are small. However, the shared controller uses a measure of human intent. When this measure reaches a threshold value, the system abandons the existing trajectory and switches to a new one. To test our ideas, a shared control simulation was developed.

The equation of motion for the force feedback controller joystick angle θ is modeled as

$$I\ddot{\theta} + b\dot{\theta} = \tau, \tag{1}$$

where I is the mass moment of inertia about the θ axis, b is the coefficient of friction and τ is an input torque.

Taking the Laplace transform of (1) a transfer function between the input torque and output angle can be found

$$G_j(s) := \frac{\Theta}{\mathcal{T}} = \frac{1/b}{s(sI/b+1)}, \tag{2}$$

where s is the Laplace transform variable, $\Theta(s) := \mathscr{L}\{\theta(t)\}$, $\mathcal{T}(s) := \mathscr{L}\{\tau(t)\}$ and t is time.

If the joystick is implemented in a unity feedback closed loop system with a unity gain proportional controller, the error is related to the commanded input angle $\theta_c(t)$ as

$$E(s) = \frac{\Theta_c(s)}{1+G_j(s)}, \tag{3}$$

where $\Theta_c(s) := \mathscr{L}\{\theta_c(t)\}$. When the commanded angle is a ramp input such that $\theta_c(t) = \dot{\theta}_0 t$ (i.e. constant motor speed $\dot{\theta}_0$), the the Final Value Theorem can be used to determine the steady state error as

$$e_{\text{ss}} = \lim_{s\to 0} \frac{s\dot{\theta}_0/s^2}{1+G_j(s)} = b\dot{\theta}_0. \tag{4}$$

Thus, the joint friction can be determined by experimentally measuring the steady state error to a ramp input and dividing by the commanded motor speed. A series of such experiments was performed with the joystick. A representative example can be seen in Fig. 1a. Based on the measurements, the joystick friction is taken to be $b = 0.254$ N-m-sec.

The mass moment of inertia of the joystick can be determined by looking at the dynamic response of the system. The transfer function (2) has a break frequency at $\omega_b = b/I$. At this frequency, the phase angle between the response and input will be $-3\pi/4$. By oscillating the joystick at various frequencies that span ω_b and measuring the phase angle between the input signal to the joystick motor controller and the output, as measured by the potentiometer, the break frequency was identified as $\omega_b = 0.33$ rad/sec. Thus, the associated mass moment of inertia of the joystick is $I = 0.762$ kg-m^2.

A simplified USV model was also developed. The model ignores many of the dynamics of a real vessel, such as nonlinear drag terms, Coriolis and centripetal forces, and side slip, but is anticipated to be adequate for exploring shared control. The linearized, one degree of freedom equation for yaw is

$$(I_z - N_{\dot{r}})\ddot{\psi} - N_r\dot{\psi} = N_\delta \delta_R, \tag{5}$$

where I_z is the mass moment of inertia about the z-axis, $N_{\dot{r}} < 0$ is the added mass moment of inertia about the z-axis, ψ is the heading angle, $N_r < 0$ is the linear coefficient of drag moment, N_δ is a yaw moment coefficient related to a rudder and δ_R is the rudder angle. For the control model it will be assumed that the maximum rudder deflection is $\pm 15°$.

Taking the Laplace transform of (5) gives

$$(I_z - N_{\dot{r}})s^2\Psi - N_r s\Psi = N_\delta \Delta_R, \tag{6}$$

where $\Psi(s) := \mathscr{L}\{\psi(t)\}$ and $\Delta_R(s) := \mathscr{L}\{\delta_R(t)\}$.

Assuming small lateral deviations from a straight-line trajectory (e.g. $\psi \ll 1$) and a constant forward speed U, then the speed along the trajectory in an Earth-fixed reference frame is

$$\dot{X} = U\cos\psi \approx U, \quad \text{and} \quad \dot{Y} = U\sin\psi \approx U\psi. \tag{7}$$

Taking the Laplace transform of (7) gives $sY/U = \Psi$, where $Y(s) := \mathscr{L}\{y(t)\}$. Using this in (6), a single-input, single-output (SISO) transfer function can be written for the USV with the rudder angle as input and the lateral deviation as output

$$\frac{Y}{\Delta_R} = \frac{\dfrac{-N_\delta U}{(I_z - N_{\dot{r}})}}{s^2\left[s - \dfrac{N_R}{(I_z - N_{\dot{r}})}\right]}. \tag{8}$$

Based on previous experience conducting on-water experiments with USVs, the terms in (8) were selected to provide a lateral deviation of $Y = 5$ m after 10 sec with a speed of $U = 1.5$ m/s and a rudder deflection of $\delta_R = 15°$, as

$$\frac{Y}{\Delta_R} = \frac{U/100}{s^2(s + 5/4)}. \tag{9}$$

A lead compensator with the transfer function

$$D(s) = \frac{K_0(s+z)}{(s+p)} \tag{10}$$

where $K_0 = 1619$, $p = 26.49$ and $z = 0.2667$, is used to ensure that the USV model can track a desired trajectory Y_{ref}, as shown in Fig. 1b. The closed loop system has a settling time of about 16 secs.

The shared control system in Fig. 2 was implemented in simulation. Results show that the stability of the system depends on the switching time between trajectory changes.

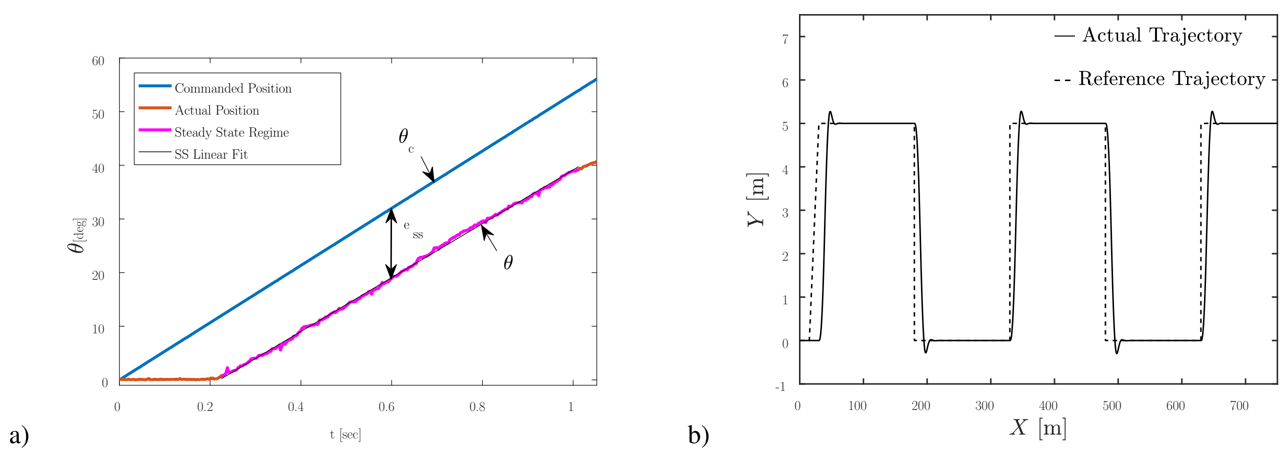

Fig. 1. a) Measurement of the steady state error to ramp input to determine joystick friction coefficient. b) Reference trajectory and actual trajectory of the closed loop USV model with dynamic compensator.

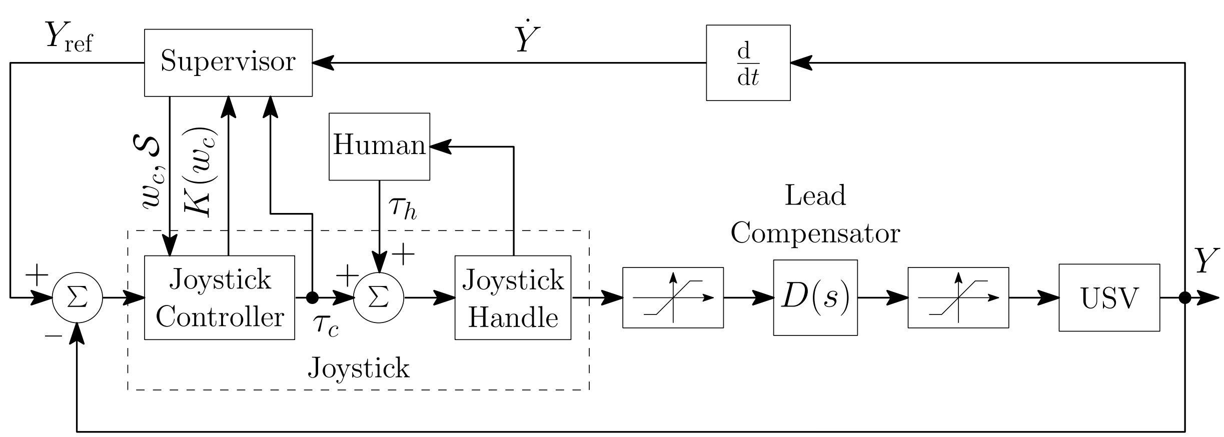

Fig. 2. Block diagram of shared control system.