Multivariable Submarine Control System Analysis and Design Using an Interactive Visualization Tool

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Abstract

This paper describes an *Interactive Modeling, Simulation, Animation, and Real-Time Control (MoSART) Environment* which may be used for analyzing, designing, visualizing, and evaluating the performance of robust multivariable submarine control systems. The described *MoSART* environment is based on Microsoft Windows NT/95/98, Visual C++, Microsoft Direct-3D, and MATLAB/SIMULINK. The environment consists of several key modules: (i) a program user-interface (PUI) module, (ii) a real-time simulation (RTS) module, (iii) a graphical visualization and animation (GVA) module, and (iv) a help/instruct module. The environment also accommodates data exchange with MATLAB. This is useful for control system analysis and redesign. This makes the developed environment very extensible with respect to mathematical modeling and control. The developed *Interactive MoSART Submarine Environment* is shown to be a valuable tool for enhancing the analysis and design process. Examples are presented to illustrate its utility.

1 Introduction

The Need For Design Tools. When a submarine is deeply submerged, the dynamic forces and moments acting on the submarine make ship control difficult [2], [11]. Traditionally, submarine control systems are designed by assuming decoupled longitudinal and lateral dynamics, using classical single-input single-output (SISO) "shaping" techniques [7], and then modifying the resulting design to accommodate cross-coupling effects. Because of increased performance requirements, the need for systematic multivariable control system design techniques [13], [14] which suitably accommodate multiple-input multiple-output (MIMO) cross-coupling effects and uncertainty have become essential. Since control system design is a highly iterative process, tools which facilitate the evaluation and "visualization" of MIMO control laws are invaluable to designers. Given this, tools which simultaneously accommodate interactive modeling, simulation, analysis, graphical visualization, animation, design, and real-time control features are of particular use to designers. Only until very recently, the development of such tools has been restricted to mainframe and workstation platforms.

Contributions of Work. This paper demonstrates how affordable state-of-the-art PC technologies may be combined to develop high quality system-specific *Interactive MoSART Environments* which are useful for enhancing the control system design process. Such environments permit control system engineers to analyze, design, and visualize the performance of submarine control systems via real-time and faster-than-real-time animation. Through a user-friendly graphical interface, users can alter model, controller, and signal parameters on-the-fly while commands are issued by a program function generator. One major feature of our environment is the ability to access the MATLAB 5.0 engine - giving the environment direct access to the MATLAB toolbox suite of numerical tools (e.g. optimization, system identification, signal processing, etc.). These features make the environment an ideal centerpiece for a highly extensible virtual design and test platform. The utility of the environment is clearly demonstrated within this paper through examples addressing fundamental control issues which are of concern to submarine navigators.

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2 Submarine Model and Control Laws

This section describes mathematical models which are implemented within our *Interactive MoSART Submarine Environment*. These models include submarine dynamical equations and MIMO control laws.

Submarine Model. The motion of a submarine is described by six degrees of freedom: three translational degrees of freedom and three rotational degrees of freedom. The submarine equations of motion (plant) implemented within the developed environment take the form

$$\dot{x}_p \;=\; A_p x_p + B_p u_p \quad y_p \;=\; C_p x_p \tag{1}$$

where the control vector $u_p \in \mathcal{R}^{4\times 1}$, state vector $x_p \in \mathcal{R}^{8\times 1}$, and output vector $y_p \in \mathcal{R}^{4\times 1}$ are given by:

$$u_p = \begin{bmatrix} db - \text{fairwater plane def} & \text{(rad)} \\ dr - \text{rudder def} & \text{(rad)} \\ ds_1 - \text{port stern plane def} & \text{(rad)} \\ ds_2 - \text{starboard stern plane def} & \text{(rad)} \end{bmatrix} \tag{2}$$

$$x_p = \begin{bmatrix} u - \text{axial velocity} & \text{(ft/sec)} \\ v - \text{lateral velocity} & \text{(ft/sec)} \\ w - \text{heave velocity} & \text{(ft/sec)} \\ p - \text{roll rate} & \text{(rad/sec)} \\ q - \text{pitch rate} & \text{(rad/sec)} \\ r - \text{yaw rate} & \text{(rad/sec)} \\ \phi - \text{roll} & \text{(radians)} \\ \theta - \text{pitch} & \text{(radians)} \end{bmatrix} \tag{3}$$

$$y_p = \begin{bmatrix} \phi - \text{roll Euler angle} & \text{(rad)} \\ \theta - \text{pitch Euler angle} & \text{(rad)} \\ \dot{\psi} - \text{yaw Euler rate} & \text{(rad/sec)} \\ \dot{z} - \text{depth rate} & \text{(ft/sec)} \end{bmatrix} \tag{4}$$

The model represents a linearization of the nonlinear dynamical equations about a 15 knot forward speed and 1 degree roll angle equilibrium [2]. Other mathematical models are also available within the developed submarine environment [10].

Model Analysis. The system poles and multivariable transmission zeros are given in Table 1. From Table 1, it follows that the submarine is stable - having all of its poles in the left half plane.

Control Laws. Several control laws are implemented within our environment. More generally, because of the easy access to the MATLAB engine from within our environment, users may seamlessly submit a model to MATLAB, generate a design, download the design into the environment, and then simulate, animate, etc. A user may also drive our animation module with a general SIMULINK-generated block diagram. This makes the environment highly extensible. In order to focus the exposition, this paper will restrict specific discussions to control laws having the structure indicated in Figure 1. In this figure, P is represents the submarine to be controlled, y represents the system output, r is a *reference command* and represents the desired system output, e is an error signal to be processed by a *compensator* K (to be designed), u is the control signal generated by K, d_i is a disturbance at the plant input, d_o is a disturbance at the plant output, and n represents sensor noise.

Pole Description	Poles	Tran. Zeros
Roll Oscillation:	$\lambda_{1,2} = -0.106 \pm j0.381$	$z_1 = -0.1273$
Roll-Yaw Subsidence:	$\lambda_3 = -0.2476$	$z_2 = -0.0190$
Horizontal Subsidence:	$\lambda_4 = -0.0206$	
Pitch Oscillation:	$\lambda_{5,6} = -0.020 \pm j0.014$	
Roll-Speed Subsidence:	$\lambda_7 = -0.0335$	
Pitch Subsidence:	$\lambda_8 = -0.2204$	

Table 1: Plant Poles and Transmission Zeros

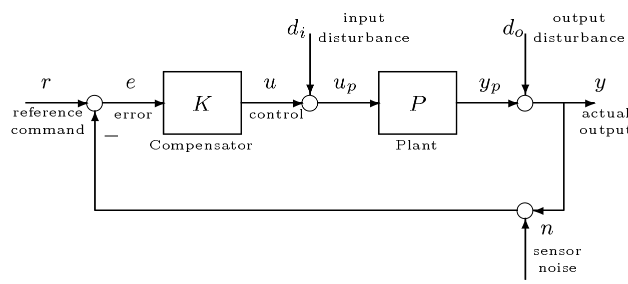

Figure 1: Standard Negative Feedback System

LQG/LTR Design. In section 4, we examine an LQG/LTR model based compensator having the form;

$$K(s) = \frac{K_{MBC}(s)}{s}. \tag{5}$$

where

$$K_{MBC} = G(sI - A + BG + H(C - DG))^{-1}H \tag{6}$$

$$A \;=\; \begin{bmatrix} A_p & B_p \\ 0 & 0 \end{bmatrix} \qquad B \;=\; \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{7}$$

$$C \;=\; \begin{bmatrix} C_p & 0 \end{bmatrix} \qquad D \;=\; 0 \tag{8}$$

where the filter gain matrix H is used to design a "target" loop transfer function matrix ($G_{KF} = C(sI - A)^{-1}H$) at the plant output and the control gain matrix G is used to "recover" the above "target loop".

H_∞ Design. In section 4, we also examine an H_∞ based controller which satisfies the following performance criterion [14]

$$\left\| \begin{array}{c} W_1 S \\ W_2 R \\ W_3 T \end{array} \right\|_{H_\infty} < \gamma \qquad (9)$$

where $S = [I + PK]^{-1}$, $R = KS$, and $T = PKS$. Here, W_1, W_2, W_3, are design parametersweighting functions specified by the designer. W_1 is typically selected to achieve good low frequency command following and disturbance rejection. W_2 is typically selected to limit control action. W_2 is typically selected to achieve high frequency noise attenuation and robustness with respect to multiplicative modeling errors at the plant output [14]. γ is another design parameter avalable to the designer which is typically selected as small as possible.

3 MoSART Submarine Environment

The *Interactive MoSART Submarine Environment* is an interactive application for simulating and visualizing a variety of complex submarine systems. The software runs on any PC-compatible computer running Microsoft Windows '95/98 or NT. For optimum performance, a fast Pentium processor and 3D-accelerated video card is recommended.

Program User Interface Module (PUI). The program user interface module (PUI) provides an interface to the user (Figure 2). A user can, for example, (i)select/edit a simulation model. (ii)select an animation model. (iii)select/edit simulation reference commands, disturbances, and sensor noise. (iv)view/alter the simulation parameters. (v)select/alter control laws, control law parameters, and control law design parameters for control law design using MATLAB/Toolbox engines. Menu options for data storage and plotting also exist. User-selected variables saved from an earlier simulation may be plotted alongside current simulation data. An active child window contains a block-diagram representation of the complete dynamical structure which has been implemented within the environment.

Simulation Module (SIM). The simulation module (SIM) was written in C++ and is optimized for speed and accuracy. It utilizes recursive algorithms which numerically solve the ordinary differential equations describing the system, control law, sensor dynamics, and signal filters. When operating in linear-simulation

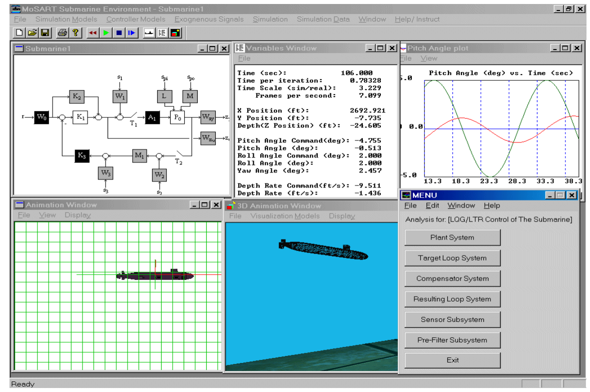

Figure 2: Visualization of Program User Interface (PUI): System Diagram, Real-Time Variable Display Window, Real-Time Graphics, 2D/3D Animation, and Access to Matlab Engine

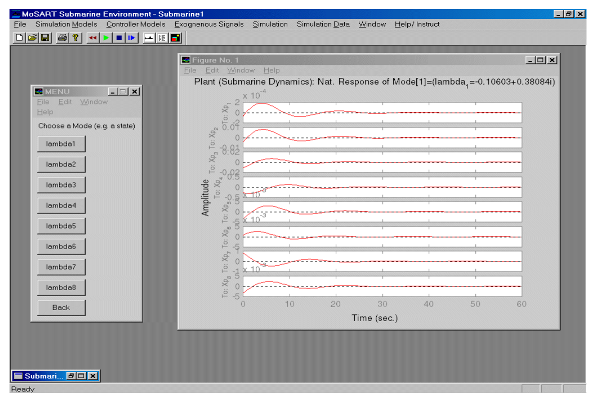

Figure 3: Plant Modal Analysis Obtained by Accessing Control System Toolbox from within Environment

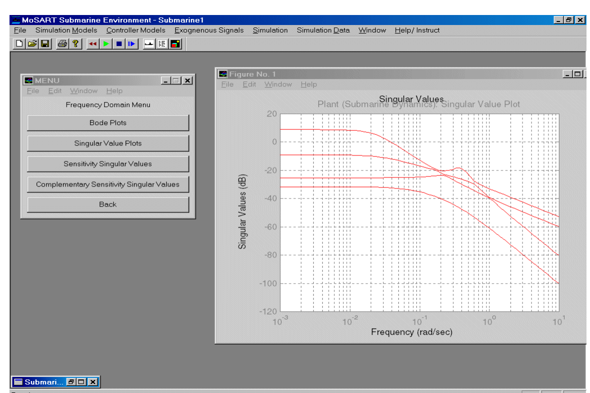

Figure 4: Plant Frequency Response Analysis Obtained by Accessing Control System Toolbox from within Environment

mode, the engine exploits a matrix-algebra C++ class toolset specifically developed for this application. Users can select - via the PUI - from different integration methods, integration method parameters, control laws, control law parameters, control law design parameters for redesign using MATLAB engine, exogenous signals, and other parameters. More complex simulations may be developed and can take advantage of direct access to MATLAB 5.0 scripts and toolboxes using the environment's *MATLAB Engine Communication Link*. Figures 3, 4 illustrate the type of analysis that may be conducted from within our *Interactive MoSART Submarine Environment* by accessing the MATLAB engine and toolboxes.

Graphics/Animation Module (GAM). The main purpose of the graphics/animation module (GAM) is to update graphics and animations using data provided by the simulation module. Data, graphs, visual indicators, and animations are displayed within child windows. The ability to visualize the simulation via various visual aids is a key feature of this environment. Several visual representations of the simulation are available to the user, including: a real-time variable display window, real-time graphing windows, and 2-dimensional and 3-dimensional Direct-3D animation windows.

Help/Instruct Module (HIM). This help/instruct module (HIM) allows for the inclusion of on-line model documentation and tutorials. It also contains basic help information for using the environment. With the inclusion of direct links to Hypertext-Markup Language (HTML) format documents, users can call up help and information directly from the environment. This allows the creation of detailed on-line model documentation, tutorials, and interactive lessons.

4 Utility of Environment

In this section, the utility of the environment as a research tool is demonstrated. Two designs (LQG/LTR and H^∞) were obtained via the environment's communication link with MATLAB. The low frequency command following properties of the designs were examined using the environment and its link to MATLAB.

LQG/LTR Design. The bandwidth parameter μ and recovery parameter ρ [10] were selected as follows:

$$\mu \;=\; 130, \qquad \rho \;=\; 10^{-9} \tag{10}$$

so that the resulting bandwidth is approximately $\omega \approx 0.1$ rad/sec. To evaluate this design in terms of low frequency command following, the following command scenario was examined:

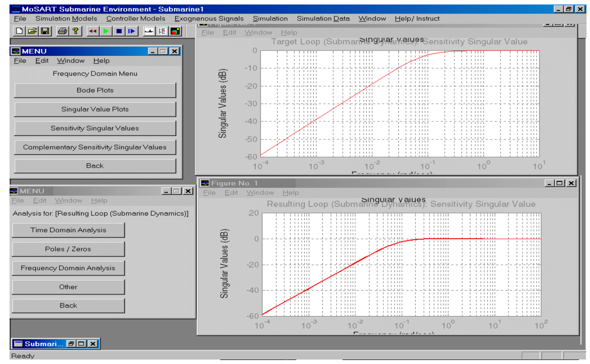

Figure 5: Target and Recovered Sensitivity Singular Values for LQG/LTR Design

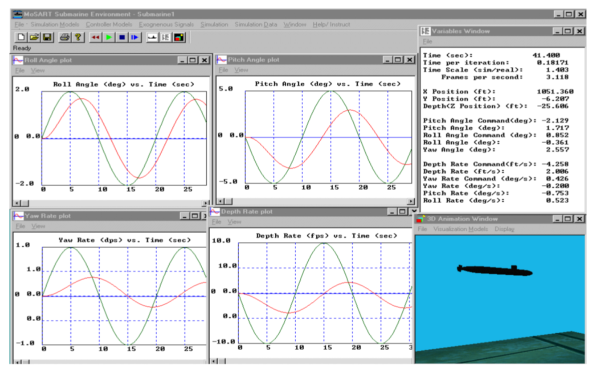

Figure 6: Command Following for LQG/LTR Design

Roll Command:	$\phi_c(t) = 2\sin(0.05t + \theta_1)$ deg;
Pitch Command:	$\theta_c(t) = 5\sin(0.05t + \theta_2)$ deg;
Yaw Rate Command:	$\dot{\psi}_c(t) = \sin(0.05t + \theta_3)$ deg/sec;
Depth Rate Command:	$\dot{z}_c(t) = 10\sin(0.05t + \theta_4)$ ft/sec.

where t is measured in seconds. This command scenario results in Figures 5, 6. Figure 5 shows the target and recovered sensitivity singular values for the design. Figure 6 show the resulting outputs.

H_∞ **Design.** The weighting functions W_1, W_22, W_3, and the design parameter γ were selected as follows:

$$W_1 \;=\; \frac{0.005(s+0.67)}{(s+10^{-6})(s+0.07)} \tag{11}$$

$$W_2 \;=\; 0.01 \tag{12}$$

$$W_3 \;=\; \frac{(s+0.0002)(s+0.12)}{0.152(s+0.0015)} \tag{13}$$

$$\gamma \;=\; 1.22 \tag{14}$$

so that the resulting bandwidth is approximately $\omega = 0.1$ rad/sec. To evaluate this design in terms of low frequency command following, the command scenario used to evaluate the LQG/LTR design was used. This command scenario results in Figures 7, 8. Figure 7

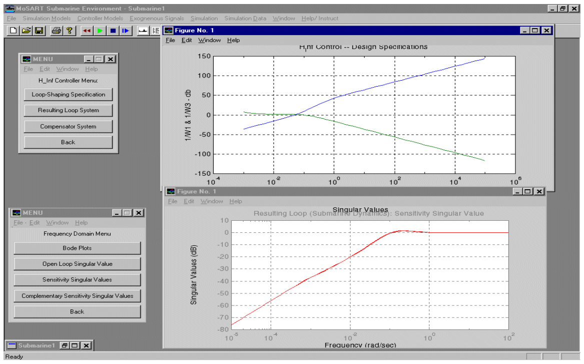

Figure 7: Design Specifications and Resulting Sensitivity Singular Values for H_∞ Design

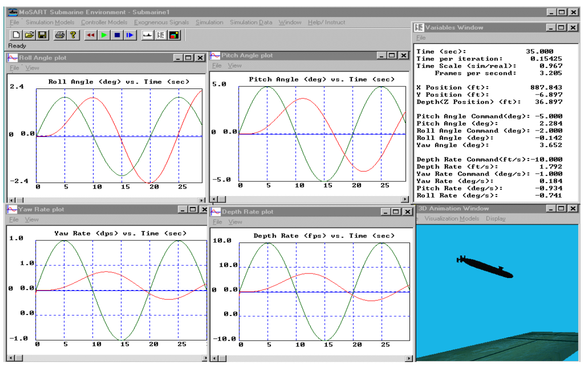

Figure 8: Command Following for H_∞ Design

shows the design specifications and the resulting sensitivity singular values for for the new design. Figure 8 shows the resulting outputs. The user can use the environment to analyze or compare the performance of different design parameters or controller interactively.

5 Summary and Future Directions

This paper has described a Microsoft Windows '95/98/NT and Visual C++ based on software environment for simulating and visualizing submarine control system. Among various types of MIMO designs, LQG/LTR and H_∞ have been popular methods for control applications. The submarine model based on a nominal point of 15 knots forward speed and 1 degree roll angle scaled for units and input/output weightings. The MoSART program may be used as a tool for demonstrating how parameter variations affect algorithm effectiveness and efficiency. With the ability to interact with the simulation in real-time and see the results quickly, the user can easily analyze and design the submarine control systems. Future work will include other MIMO control design methods (e.g. LQ Servo, neural network control and nonlinear control methods (e.g. sliding control model) for the submarine control. The interactive MoSART submarine environment will serve as a platform supporting the above other control methods. To realizing it, the powerful MoSART environment is need for very complex simulation, animation, and control models. Also, this will be the focus of future work.

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