A comparison of classical, neural and fuzzy control

for an underwater vehicle

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Abstract: - A comparative study for the automatic control of an underwater vehicle has been conducted. The vessel had only three thrusters for the control of its position, something that made the problem very difficult. Furthermore the system is highly non-linear. A control system has been simulated for the regulation of the marine thrusters so that they stabilize the vehicle at a desired position, irrespective of external disturbances. The dynamical equations of a model of the vessel, when disturbed by cable forces and by the thrusts generated by the propellers, are described. The various vehicle parameters needed to describe its dynamics (mass, center of mass, added coefficients) have been estimated. The control schemes implemented were the classical PID, neural control, and fuzzy control. It was found that a combination of classical and intelligent control gave the best results.

Key-Words: - Artificial Neural Network Control, Fuzzy Control, Nonlinear Systems. Underwater Vehicle Control

1 Introduction

Remotely operated underwater vehicles, both autonomous and non-autonomous, can be used in diverse missions. They are especially useful in areas that are dangerous for human operations, and in locations where the accessibility is restricted. Also in the cases where the hazards are diverse and serious such as in underwater monitoring, positioning, surveyance etc. The development of simple and efficient control systems for such remotely operated vessels is not an easy task. A number of studies have been done on the control of non-holonomic vehicles (Hunt et al., 1992; Narendra and Muk-hopadhyay, 1997; Tanner and Kyriakopoulos, 2001; Li et al., 2004).

For the particular problem on the control of a remotely operated manipulator that has been examined and reported in this paper, there were no constraints in the motion of the vehicle. The

problem though is quite difficult because there were only three actuators available to guide the vessel to the desired position and maintain it in this location. The available actuators were: a) two small thrusters at the stern, one at port and the other at starboard that could be used to control the forward, backward and yaw of the vessel b) a top thruster that could be used to control the underwater motion along the vertical direction.

2 Dynamics of the underwater vehicle

The system has been modeled as a mass that is affected by various external forces as it is free to move in the 3D space. The external forces are quite complicated to estimate as they are non linear and may include inertia effects from the so-called added mass and damping. The dynamics that have been used are mainly based on the analysis presented by various researchers (Fossen, 1995; Buckham et al., 2002; Ridley et al., 2002; Smallwood and Whitcomb, 2004). They are described by a system of six coupled non-linear differential equations.

The general form of the dynamical equations describing the motion of the vehicle, with respect to an inertial frame of reference, is given by (Fossen, 1995) as:

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}\mathbf{v} + \mathbf{D}\mathbf{v} + \mathbf{g} = \mathbf{F}_{ext} \qquad (1)$$

where,

$\mathbf{M}$ = Matrix of the system masses and the added masses.

$\mathbf{C}$ = Matrix whose elements are the centripetal acceleration and the Coriolis components of acceleration.

$\mathbf{D}$ = Matrix whose elements are the components of damping.

$\mathbf{F}_{ext}$ = External force vector.

$\mathbf{v}$ = Velocity vector.

$\mathbf{g}$ = Vector whose elements are the gravitational and buoyancy forces.

In general the elements of $\mathbf{g}$ are dependent on the position of the vessel, while the elements of $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{D}$, on the velocity components.

The system of equations 1 can be expanded in a more convenient form that is more suitable for modeling on MATLAB-SIMULINK and for the necessary simulations. To do this, we used the Euler angle formalism as well as the rotation matrix $\mathbf{J}$ shown in equation 2.

Because of the constraints imposed by the fact that only three actuators are available to guide the vessel, as well as the symmetry of the vessel, its motion is confined to be in the three principal directions x, y, and z of a body frame, as well as rotation about the z axis. Rotations about the x and y axes cannot exist, so that they are not included in the equations of the system that are finally used. Thus, the system of equations (1) for the 4-degree of freedom vessel, which is the case for the vessel we examined, are modified as (3), where the usual notation for transposition and inversion is used.

The terms $X_{\dot{u}}$, $Y_{\dot{v}}$, $Z_{\dot{w}}$, $N_{\dot{r}}$ are the added coefficients that have been calculated for the particular vessel we examined. Also, the terms E_1, E_2, E_3, denote the forces originating from the three thrusters, while K_x, K_y and K_z are the cable forces.

$$\mathbf{J} = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi+\cos\psi\cos\phi\sin\theta & 0 & 0 & 0 \\ \sin\psi\cos\theta & \cos\psi\cos\phi+\sin\phi\sin\theta\sin\psi & -\cos\psi\sin\phi+\sin\theta\sin\psi\cos\phi & 0 & 0 & 0 \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & 0 & 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & 0 & 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix} \qquad (2)$$

$$
\begin{aligned}
&\left[\mathbf{J^{-T}}\right]
\begin{bmatrix}
m-X_{\dot{u}} & 0 & 0 & 0 \\
0 & m-Y_{\dot{v}} & 0 & 0 \\
0 & 0 & m-Z_{\dot{w}} & 0 \\
0 & 0 & 0 & I_z-N_{\dot{r}}
\end{bmatrix}
\left[\mathbf{J^{-1}}\right]
\begin{bmatrix}
\ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\psi}
\end{bmatrix} \\[2mm]
&+\left[\left[\mathbf{J^{-T}}\right]
\begin{bmatrix}
0 & 0 & 0 & (-m+Y_{\dot{v}})v \\
0 & 0 & 0 & (m-X_{\dot{u}})u \\
0 & 0 & 0 & 0 \\
(m-Y_{\dot{v}})v & (-m+X_{\dot{u}})u & 0 & 0
\end{bmatrix}
-
\begin{bmatrix}
m-X_{\dot{u}} & 0 & 0 & 0 \\
0 & m-Y_{\dot{v}} & 0 & 0 \\
0 & 0 & m-Z_{\dot{w}} & 0 \\
0 & 0 & 0 & I_z-N_{\dot{r}}
\end{bmatrix}
\left[\mathbf{J^{-1}}\right]\left[\mathbf{\dot{J}}\right]\left[\mathbf{J^{-1}}\right]\,\right]
\begin{bmatrix}
\dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\psi}
\end{bmatrix} \quad (3) \\[2mm]
&=\mathbf{J^{-T}}
\begin{bmatrix}
E_1+E_2+K_x \\
K_y \\
E_3+K_z \\
E_1\times d-E_2\times d+K_\psi
\end{bmatrix}
\end{aligned}
$$

The system of equations (3) has been implemented in a series of models in MATLAB and SIMULINK and simulated to verify its credibility, as well as to try and compare different control schemes.

Three major groups of control schemes have been attempted and compared. In each scheme various parameters were systematically tried. The control schemes used are a) Three different classic PID controllers, one for each propeller, b) A Model Predictive Neural Network control system, c) A Fuzzy Inference System based on the MATLAB Fuzzy Logic Toolbox.

Many SIMULINK models have been built to simulate the system, its constituent components and the various control schemes. As an example, Figure 1 shows an expanded structure of the underwater vehicle subsystem.
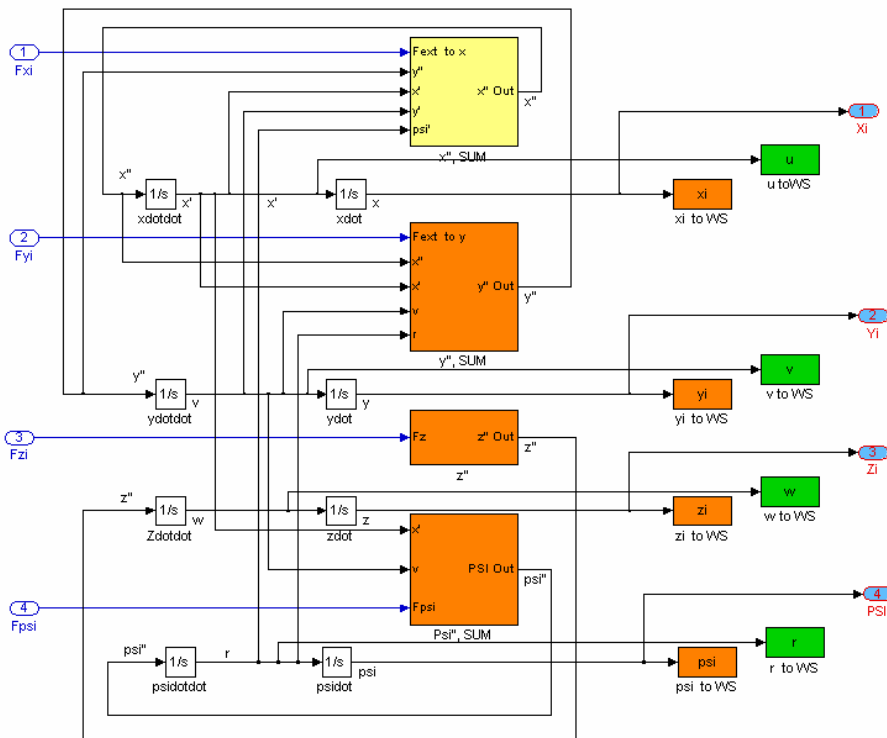

Figure 1. The underwater subsystem.

3   Results of simulations for different controller paradigms

The first control system model that has been tried is the one in which three different classic PID controllers have been used, one for each propeller. Figure 2 shows the typical results obtained when the vessel was commanded to move from an initial position of $(x_i, y_i, z_i, \psi_i)^T = (0, 0, 0, 0)^T$ to a desired new position of $(x_d, y_d, z_d, \psi_d)^T = (2, 3, -5, 0)^T$. As can be seen from this Figure, the results were not satisfactory, especially with regards to the y positioning.

The second model that has been used is a Model Predictive Neural Network as it is available in the neural networks toolbox of MATLAB, but suitably adapted to accommodate our case. The

results, again were not very good, as shown in Figure 3.

In the third case a Fuzzy Inference System based on the MATLAB Fuzzy Logic System has been employed. Due to the constraint having to maintain the paper short, some of the rules that have been used are indicatively displayed in Figure 4.

The results are show in Figure 5. In this case, a combination of a classical and a fuzzy controller has been used. The classic PID controller is used to regulate the vertical propeller generating a thrust perpendicular to the body of the vessel. The other two thrusters are controlled by the fuzzy inference controller system.

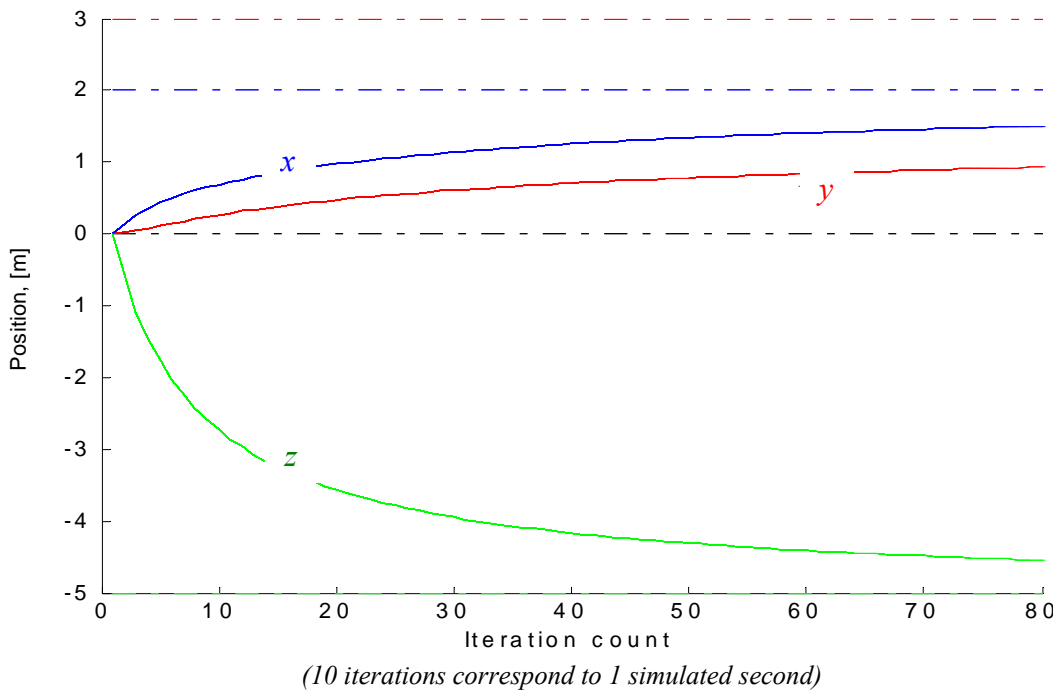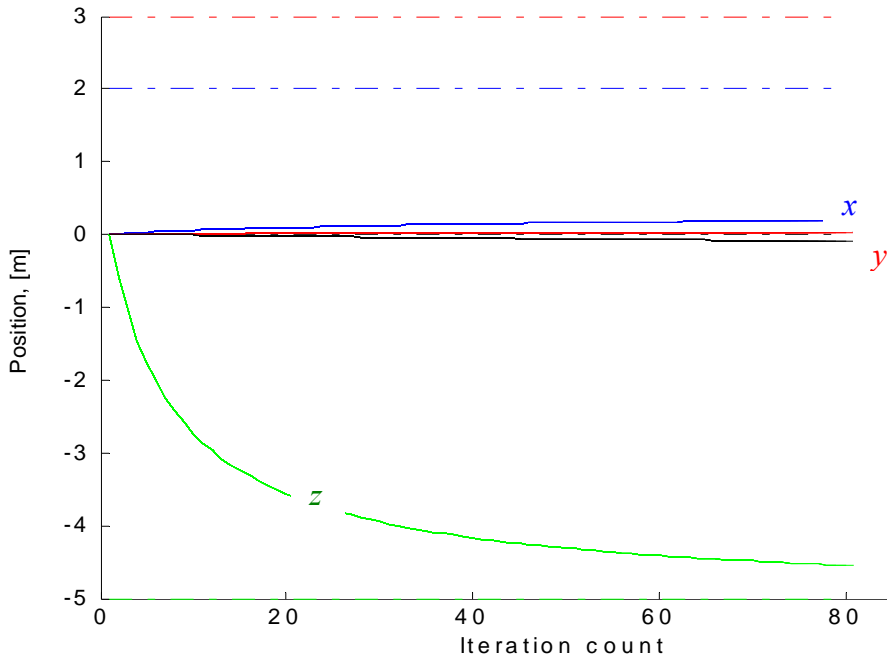It is quite clear that this case is much better than the previous two.

(10 iterations correspond to 1 simulated second)

Figure 2. Simulation results for the case of using three PID controllers.
The initial position is at **0**. The desired position vector is $\mathbf{x_d} = [2\ 3\ -5\ 0]^T$.

(10 iterations correspond to 1 simulated second)

Figure 3. Simulation results for the case of using neural network controllers.
The initial position is at **0**. The desired position vector is $\mathbf{x_d} = [2\ 3\ {-5}\ 0]^T$.
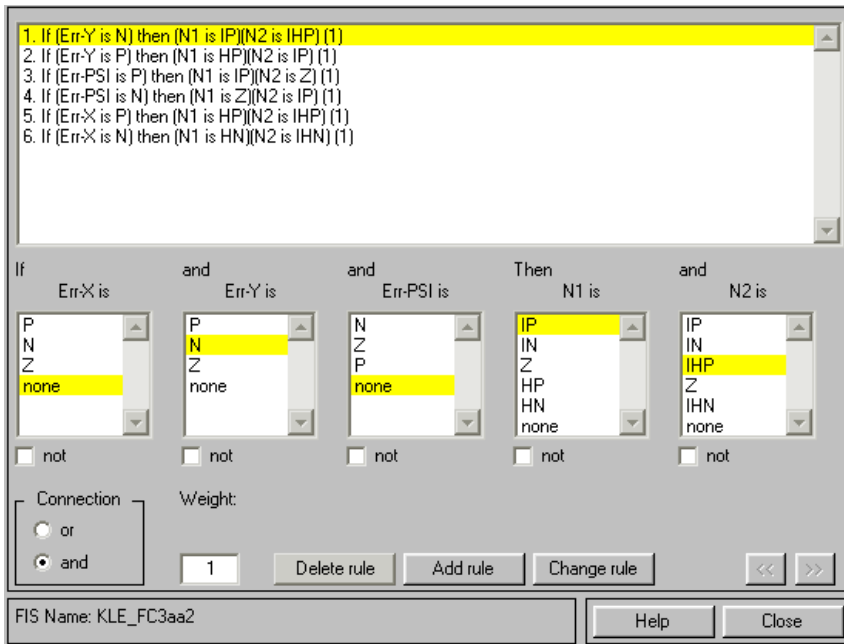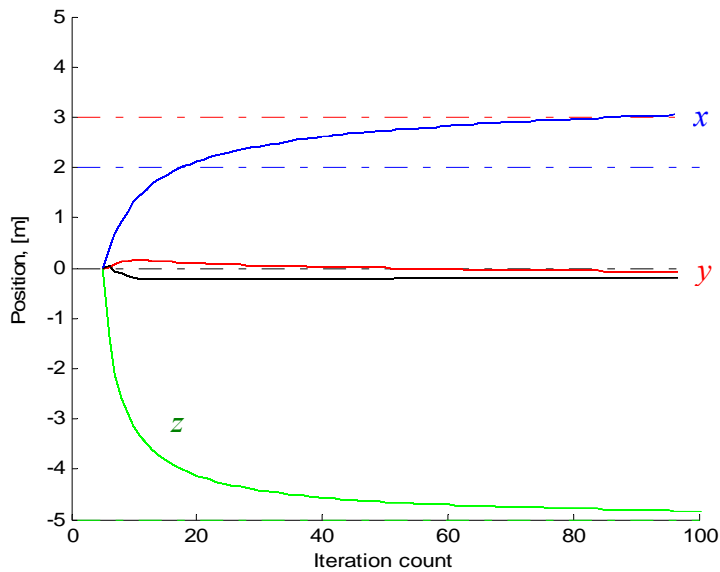

Figure 4. Some of the rules that have been used in the Fuzzy Inference System.

(10 iterations correspond to 1 simulated second)

Figure 5. Simulation results for the case of the hybrid PID-Fuzzy controller system. The initial position is at **0**. The desired position vector is $\mathbf{x_d} = [2\ 3\ -5\ 0]^T$.

4 Conclusion

The basic conclusion of this work is that when a vessel has limited actuators and highly non-linear dynamics as in our case, it is very difficult to control. One has to explore alternative schemes, and combinations of various approaches.

From the three general approaches we used, the best approach was a combination of PID and a fuzzy inference system. If we had actual experimental data on the dynamics of the vessel, as well as real feedback, the results of the neural network approach could have been better. This will be investigated in future work.

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