Fuzzy Logic Approach for Hybrid Position/Force Control on Underwater Manipulator

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Abstract

A fuzzy logic control method for hybrid position/force control of underwater manipulator is proposed in this paper. Hybrid means both position and force control is used to regulate the motion of an underwater manipulator. The main objective of this paper is to achieve a good end-effector trajectory tracking in an underwater environment. The other goal of this paper is to control the contact force whenever the end-effector comes in contact with a compliant object. Two different values of environment stiffness are applied in this case study. The experiment was conducted via MATLAB™ simulation whereby the controller was tested using underwater environment. This includes the added mass, buoyancy and drag force. The experiment includes the performance of the manipulator tracking its trajectory when there is no object, dual object and different stiffness in the object. The result indicates that the force/position controller is able to minimize the amount of error by following the desired trajectory. The system switches into the force controller once it comes in contact with a compliant object inside its working space.

1. Introduction

Most underwater manipulation task, such as underwater pipeline or weld inspection, surveying, cable burial and mating of underwater connector, require the manipulator mounted on the vehicle to come into contact with the underwater object or environment [1]. The precise and robust operation of such manipulator system is a challenging task, mainly due to the uncertainties of the system dynamic model and the unstructured nature of the underwater environment. The manipulator performance is determined by the control scheme which is applied to it. There are various methods designed in order to control the movement of the robotic manipulator. The mechanical design and configuration design will also impact the performance of the manipulator. In underwater tasks, the end-effector of the manipulator is required to come into contact with the underwater environment and exert certain force on it. The environment itself sets constraints on the desired end-effector trajectory and the end-effector cannot freely move in all directions. The resulting motion is usually referred to as constrained motion or compliant motion in robotics. Therefore, the manipulator is required not only to control the position, but also to control the force in some direction with the environment. To get the purpose of position and force control, many hybrid position/force control method have been developed. In this approach control law switching is required to obtain compliance for the manipulator. This paper will analyze a hybrid position/force control using fuzzy logic control method in underwater environment when the manipulator moves and contacting with different stiffness of environment (compliant object). Fuzzy control has a good potential for nonlinear, highly coupled, and time variant system [2]. The dynamic coupling between the manipulator and the vehicle is not considered in the system model.

2. Dynamics model of Underwater Manipulator

Two-link planar manipulator (Fig. 1) is designed and its dynamic equation is derived using Lagrange formulation. Fig. 1 also has illustrated the compliant object attached on the end-effector. $\boldsymbol{d}$ and k_c on the Fig. denote deformation vector of compliant object and coefficient of elastic compliant object respectively. **F** is the vector of contact forces. The motion is only on vertical plane and it is assumed fully submerge. The dynamics equation of motion for ordinary manipulator has been derived on [1].

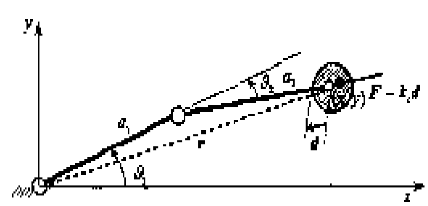


Fig. 1: Two-link planar manipulator [1]

However, in underwater manipulator, the hydrodynamics factors that existed in the underwater environment must be considered. This includes the added mass, buoyancy, and drag. Added mass is the effect of fluid inertia in the environment on a moving body. The added mass coefficient is dependent on body geometry and motion. Buoyant force is defined as equal to the weight of the fluid displaced by Archimedes's principle. Fluid viscosity creates drag and lift forces on a body. Drag acts in parallel with the flow velocity on the body. The derivation of hydrodynamic parameters is referred on [3], [4], [5]. After all those hydrodynamic parameters have been added, the new dynamics equation is described in Equation [1]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + h(q) + u_d + F_c + F_{mfr} = u \qquad [1]$$

Where q is the n x 1 joint angle vector, M(q) is the n x n inertia matrix $C(q,\dot{q})$ is the n x n Coriolis matrix, h is the gravity and buoyancy factor and u_d is the drag force , F_c is the contact force and F_{mfr} is the force from the motor friction. u is the input torque.

$$M(q)=\begin{bmatrix} l_2^2 m_{a2} + 2l_1 l_2 m_{a2} c_2 + l_1^2(m_{a1}+m_{a2}) & l_2^2 m_{a2} + l_1 l_2 m_{a2} c_2 \\ l_2^2 m_{a2} + l_1 l_2 m_{a2} c_2 & l_2^2 m_{a2} \end{bmatrix} \qquad [2]$$

$$C(q,\dot{q}) = \begin{bmatrix} -m_{a2} l_1 l_2 s_2 \dot{q}_2 & -m_{a2} l_1 l_2 s_2 (\dot{q}_1 + \dot{q}_2) \\ m_{a2} l_1 l_2 s_2 \dot{q}_1 & 0 \end{bmatrix} \qquad [3]$$

$$h(q)= \begin{bmatrix} (m_2 - \nabla_2) l_2 g c_{12} + (m_1 + m_2 - \nabla_1 - \nabla_2) l_1 g c_1 \\ (m_2 - \nabla_2) l_2 g c_{12} \end{bmatrix}, \qquad [4]$$

∇ is the mass of water displaced by the link

$$U_{d(i)} = \frac{\rho C_d A_s}{2} \int_0^l x |V_i(x)| V_i(x) dx \qquad [5]$$

ρ is the water density, C_d, is the drag coefficient, A_s is the Area surface, V(x) is the velocity normal to the link

$$F_c = \begin{bmatrix} (l_1 s_1 + l_2 s_{12}) k_c d - (l_1 c_1 + l_2 c_{12}) k_c d \\ (l_2 s_{12}) k_c d - (l_2 c_{12}) k_c d \end{bmatrix}, \qquad [6]$$

$s_{ij} = \sin(\theta_1+\theta_2)$ and k_c is the elastic compliant object

$$F_{mfr} = \begin{bmatrix} k_{fm1}\dot{\theta}_1 \\ k_{fm2}\dot{\theta}_2 \end{bmatrix}, \; k_{fm} \text{ is the motor friction coefficient} \qquad [7]$$

Below are the parameters values of manipulator and joint actuators:

$a_1=a_2=1$m, $rad_1=rad_2=0.05$m, $I_{l1}=I_{l2}=10$kg.m^2,
$L_1=L_2=1$m, $I_{m1}=I_{m2}=0.01$kg.m^2, $m_{m1}=m_{m2}=5$kg,
$k_{r1}=k_{r2}=500$ $m_1=m_2=50$kg, $k_1= k_2=500$

where $rad_{1,2}$ are the radius of links, $I_{l1,2}$ are the moments of inertia with respect to the axes of the rotors, $L_{1,2}$ are the distances of the centers of mass of the two links from the respective joint axes, $I_{m1,2}$ are the moments of inertia relative to the centers of mass of the two links, $m_{m1,2}$ are the masses of the rotors, $k_{r1,2}$ are the gear ratio of motor, $m_{1,2}$ are the mass of two links, and $k_{1,2}$ are the coefficients of motor friction, a_1 and a_2 is the link length. The shape of links is assumed cylindrical.

3. Control system

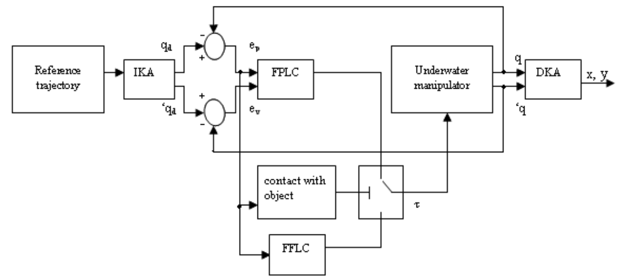


Fig. 2: Block diagram of control system

The block diagram of a control system includes force and position controllers, underwater manipulator and algorithms for computing direct and inverse kinematics are built in the Simulink environment. Transition from position control to force control occurs depend on the errors recognition by relay block where the force controller is on whenever the error reaches 0.07 and above. *IKA* and *DKA* represent the inverse kinematics and direct kinematics algorithm respectively. Fuzzy logic controllers are designed using toolbox in Matlab™. Generally, fuzzy control is an important area of real applications for the fuzzy sets theory. It is generalized form of expert control using fuzzy sets in the definition of linguistic predicates, by modeling a system with If-Then rules. A fuzzy logic system is a nonlinear system that maps a crisp input vector into a crisp scalar output. The basic methodology of fuzzy logic control does not require a precise mathematical model of the controlled object; instead it models experiences and knowledge of the operator. In fact the concept of a fuzzy logic controller is not far from that of a conventional controllers (PI, PID), except the fact that a fuzzy logic controller allows more robustness and more complex mapping.

i. Fuzzy Position Logic Controller (FPLC)

In this system, the inputs for fuzzy position controller are *position error,* e_p and *velocity error,* e_v. The output is *derivative of joint torque,* dτ. 5 linguistic variables are created for e_p, and 7 linguistic variables are created for e_v and dτ each. 7 Rules are used in FPLC which is:

If (e_p is NS) or (e_v is NS) then (dτ is PS)
If (e_p is PS) or (e_v is PS) then (dτ is NS)
If (e_p is ZE) and (e_v is ZE) then (dτ is ZE)
If (e_p is NB) or (e_v is NB) then (dτ is PB)
If (e_p is PB) or (e_v is PB) then (dτ is NB)
If (e_v is B+) then (dτ is B-)
If (e_v is B-) then (dτ is B+)

ii. Fuzzy Force Logic Controller (FFLC)

The fuzzy force controller also has two inputs; position errors of first and second joint angles (two-links), e_1 and e_2. The outputs are first and second joint torques, τ_1 and τ_2. Only 2 linguistic variables are created for each input and output. The fuzzy rules of FFLC are:

If (e_1 is PE) then (τ_1 is NE)
If (e_1 is NE) then (τ_1 is PE)
If (e_2 is PE) then (τ_2 is NE)
If (e_2 is NE) then (τ_2 is PE)

4. Case study through simulation

Extensive computer simulations are performed to investigate the effectiveness of the controllers. Several case studies are conducted to test the performance of the controllers. when manipulator moves in underwater and contacts with different stiffness of environment. The trajectory planning is designed which is to generate the reference inputs to motion control system which ensures that the manipulator executes the planned trajectory. A desired trajectory is specified in the operational space. In this paper, a half circular trajectory is designed. A trapezoidal velocity profile is assigned. Interpolation between two intermediate points is obtained on the basis of trapezoidal velocity profile.

5. Simulation Results

In the first study, the manipulator is required to move in underwater environment without constraint and accurate trajectory tracking is required in both operational and joint spaces. The assumption is made whereby it works in calm water with no disturbance.

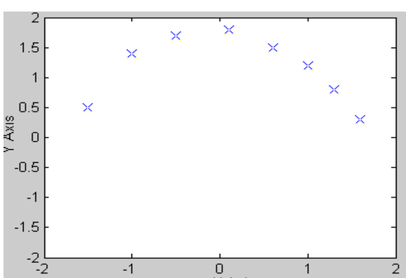


Fig. 3a : Desired position trajectory

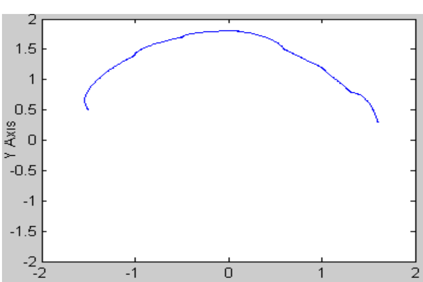


Fig. 3b : Actual position trajectory

The desired and actual position trajectory in the operational space is illustrated in Fig. 3a and 3b respectively. The desired trajectory is shown by points. Fig. 3 and 4 show the position and velocity of both joints in rad and rad/s. The joint position errors responses on Fig. 5 verify that the position controller performs good trajectory tracking because the maximum value of error is less than 0.05 radians

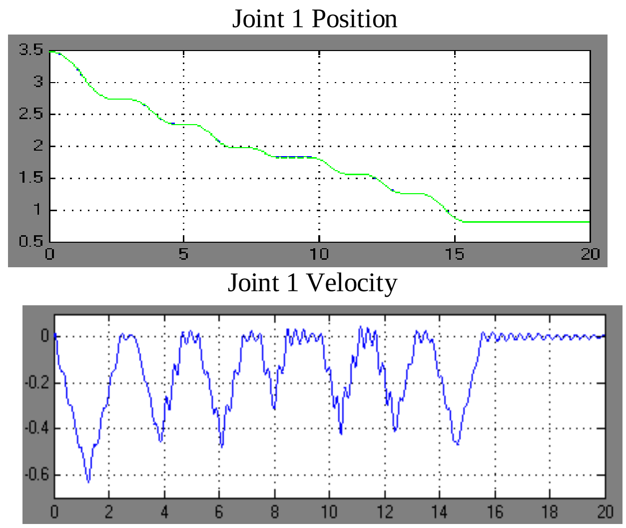


Fig. 4: Position and velocity of joint 1

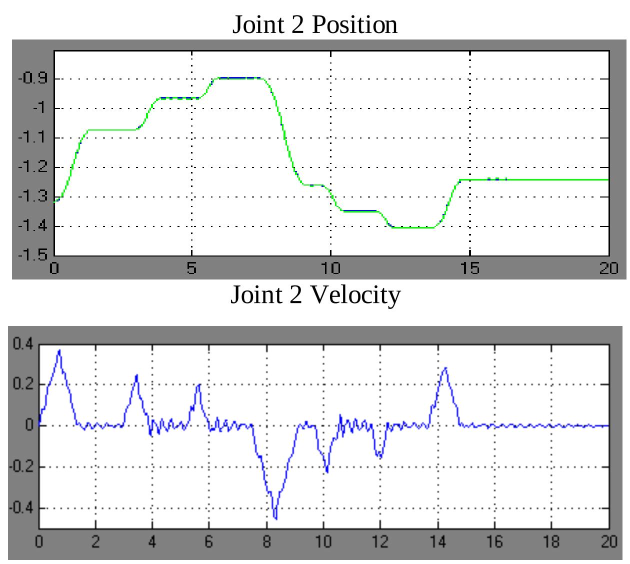


Fig. 5: Position and velocity of joint 2

Joint 1 position error

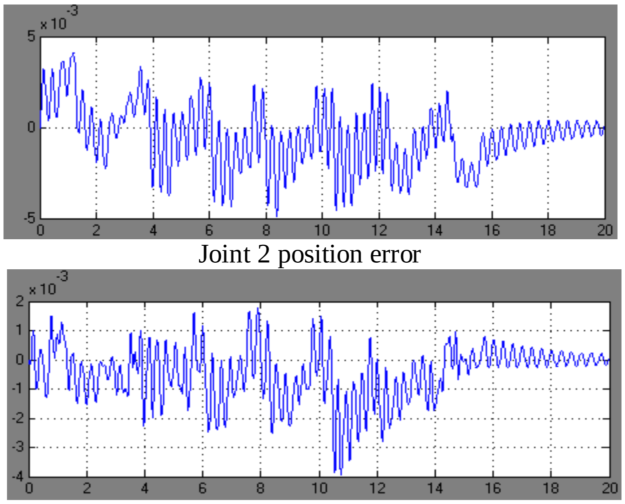


Fig. 6: Joint position tracking errors

In order to analyze the effectiveness of force controller together with the position controller, the operational space is included with two elastically complaint objects. The end-effector is considered contacts with both complaint objects on its way to follow the desired trajectory. The objects are placed such as illustrated on Fig. 7. First, both objects are set to have a same value of compliance coefficient (environment stiffness), $k_{tr1}= k_{tr2} = 1x10^3$N/m. During interaction, the position controller attempts to minimize the error which will increase the contact force. The high value contact force will stress both manipulator and manipulated object which is maybe make the system unstable or damage. In this case, the force controller is required to manipulate the desired force. In the case of $k_{tr} = 1x10^3$N/m, the en-effector can penetrates each object after 2 seconds (Fig. 8). Fig. 8 is the responses of force along x and y axis during contact. There are an overshoot on the force responses when the manipulator is trying to push the object. The overshoot is higher when contacting with larger stiffness of environment. However, the joint errors are still in small values because the manipulator able to follow the desired trajectory after accommodates the force. The required torques apply to the motor are shown on Fig. 9.

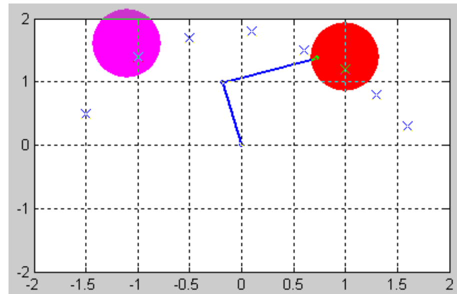


Fig. 7: Operational space with object in parallel plane

Fx

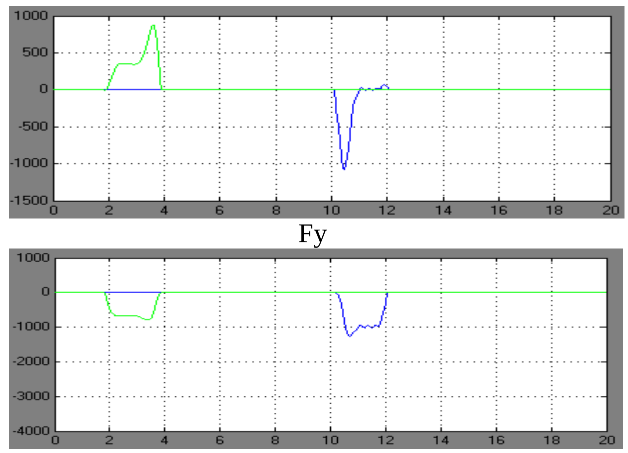


Fig. 8: Force response along x and y axis with $k_{tr1}= k_{tr2}= 1x10^3$N/m

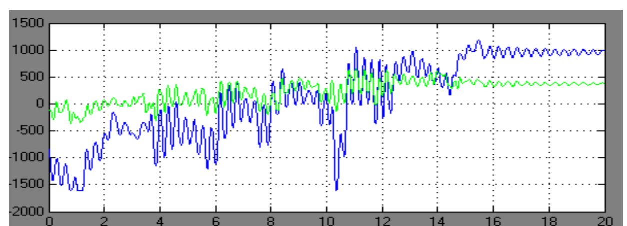
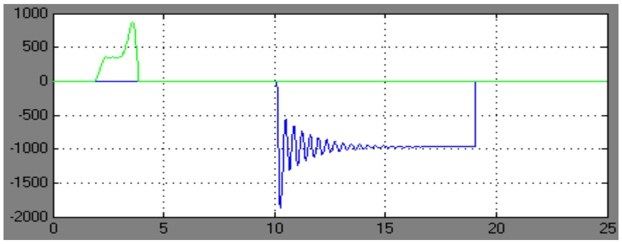


Fig. 9: Joints torques when $k_{tr1}= k_{tr2} = 1x10^3$N/m

The environment stiffness, k_{tr2} is then changed with higher value whereby $k_{tr1}= 1x10^3$N/m, $k_{tr2} = 5x10^3$N/m. When contacting with the second object, the end-effector fail to penetrate it and continue to push it. At this moment, the force controller will control forces in satisfactory manner to avoid an unstable contact case occur. After 8 seconds, the object is moved away from the end-effector. The manipulator is able to continue to follow the desired trajectory. By referring on Fig. 10, the contact force, Fx shows that at the beginning of contact, high force is applied. After that, it starts to decrease and reach steady state at a smaller value. The value of Fy is very small. Fig. 11 shows the torque responses. The errors responses illustrated by Fig. 12 verify that the manipulator still follow the trajectory even though need to accommodate with high value of environment stiffness. The high value of error occurred during the end-effector try to push the object.

Fx



Fy

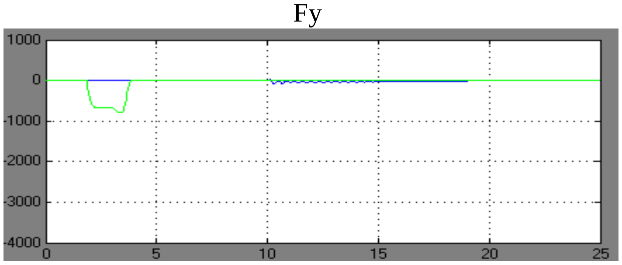


Fig. 10: Force response along x and y axis with k_{tr1}= 1x10^{3}N/m, k_{tr2} = 5x10^{3}N/m

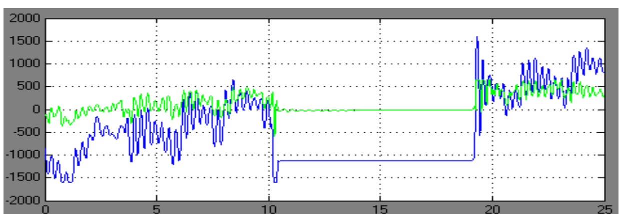
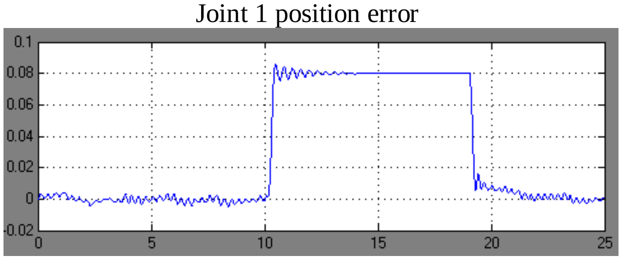


Fig. 11: Joints torques when k_{tr1}= 1x10^{3}N/m, k_{tr2} = 5x10^{3}N/m

Joint 1 position error



Joint 2 position error

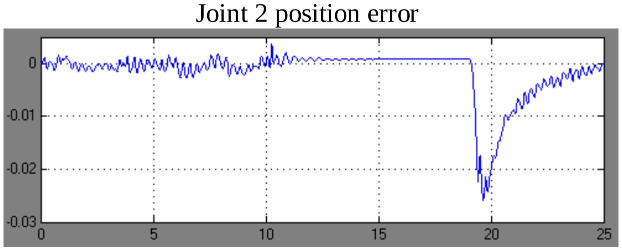


Fig. 12: Joint position tracking errors when k_{tr1}= 1x10^{3}N/m, k_{tr2} = 5x10^{3}N/m

6. Conclusion & Future Works

This paper provides a switching hybrid position/force control of an underwater manipulator using fuzzy logic approach. This controller is developed to achieve a good end-effector trajectory tracking when manipulator moves in an underwater environment and contacting with different stiffness of environment. Several case studies are conducted. The results have proved that this controller perform well and achieve the goal. Further work can be done by improving the modeling of the underwater hydrodynamics which is basically the most difficult problem. There are other available controllers which can perform nonlinear control of underwater manipulator towards the manipulator such as neural networks and sliding mode control that can be investigated.

References

[1] R K Mittal, I J Nagrath, "Robotics and Control", Tata McGraw Hill, New Delhi, 2003

[2] Jasmin Velagic, Azra Adzemovic, Jasmina Ibrahimagic, "Switching Force/Position Fuzzy Control of Robotic Manipulator", International Conference on Advanced Intelligent Mechatronics (AIM 2003)

[3] Edward M. Lewandowski, "The Dynamics of Marine Craft – Maneuvering and Seakeeping", World Scientific Publishing Co., Singapore, 2004.

[4] Thor. I. Fossen, "Marine Control Systems – Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles", Marine Cybernetics AS, Norway, 2002.

[5] Irfan A.R, Surina M.S, Mohd Rizal A., Underwater Manipulator Design Theory And Design Issues, Conference on Control Instrumentation and Mechatronics, 2007

[6] Yong Cui, Nilanjan Sarkar, "A Unified Force Control Approach to Autonomous Underwater Manipulation", International Conference on Robotics and Automation San Francisco, CA, April 2000

[7] N. Boubekri, Pinaki Chakraborty, "Robotic grasping gripper designs, control methods and grasp configurations - a review of research", Integrated Manufacturing Systems 13/7, 2002, 520-531.

[8] Gianluca Antonelli, "Underwater Robots – Motion and Force Control of Vehicle Manipulator Systems", Springer-Verlag Berlin Heidelberg Germany, 2003