JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

ADAPTIVE ROBUST CONTROL OF HYDRAULIC MANIPULATORS

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Abstract : This study has been undertaken to investigate the determinants of stock returns in Karachi Stock Exchange (KSE) using two assets pricing models the classical Capital Asset Pricing Model and Arbitrage Pricing Theory model. To test the CAPM market return is used and macroeconomic variables are used to test the APT. The macroeconomic variables include inflation, oil prices, interest rate and exchange rate. For the very purpose monthly time series data has been arranged from Jan 2010 to Dec 2014. The analytical framework contains.

Keywords**—Adaptivecontrol,electro-hydraulicsystem,motioncontrol,robustcontrol**

INTRODUCTION

Hydraulic systems are favored in industry requiring large actuation force. The direct-adaptive robust-control (DARC) technique proposed was applied for precision-motion control of an electro-hydraulic manipulator. However, being a tuning function-based Lyapunov design, it does not provide the freedom to choose parameter estimation law independent of controller design. The usual gradient-type of parameter estimation law, as used in the DARC design, may not have good convergence properties as the indirect estimation laws (e.g., the least-squares method). An indirect adaptive robust controller (IARC) design was proposed to overcome the poor parameter-estimation property of the DARC algorithm.

The modular design in the IARC algorithm allowed the use of least-squares type of estimation law to have better parameter-convergence properties and accuracies. It also achieved a complete separation of controller and estimator designs. The output-tracking performance was guaranteed by use of a robust-control law, which was independent of the parameter estimation module. Hence, when the driving signal is not persistently exciting (PE), the estimator module could be turned off without affecting the stability of the overall closed-loop system. This switching of adaptation algorithm ensures that the good parameter estimates obtained by PE signals are not corrupted by non-PE signals. The better estimation properties of such an algorithm was effectively demonstrated.

To overcome the lack of fast-integration-type-model compensation in IARC design, an integrated direct indirect adaptive robust control (DIARC) approach was proposed for a class of single-input–single-output (SISO) uncertain nonlinear systems transformable to semistrict parametric feedback form, and it has been applied for the control of linear motors and parallel manipulators driven by pneumatic muscles. In this paper, such an integrated ARC-design framework will be employed for the precision-motion control of an electro-hydraulic robotic arm driven by single-rod hydraulic actuators with valve dead band.

In addition to various unmatched model uncertainties considered, this paper also explicitly takes into account the effect of unknown valve dead band. During the past decade, various researchers have tried to solve this problem by estimating the dead band parameters using direct adaptive control algorithms. As pointed out, the unknown dead band nonlinearity cannot be linearly parameterized globally. As such, when direct adaptive control approach is used, it becomes impossible to accurately estimate the deadband parameters even when persistent exciting conditions are satisfied. Departing from these direct estimation laws, this paper will employ indirect estimation design with explicit condition monitoring of signal excitations in the proposed modified DIARC algorithm. The proposed controller design fully utilizes the fact that even though unknown deadband nonlinearity cannot be globally linearly parameterized, it can be linearly parameterized during most of the working range. This approach ensures complete adaptive compensation in the presence of parametric uncertainty only and, thus, is able to achieve asymptotic-output tracking or zero steady-state tracking errors.

I. HYDRAULIC SYSTEMS

A hydraulic system is a drive or transmission system that uses pressurized hydraulic fluid to drive hydraulic machinery. The term hydrostatic refers to the transfer of energy from flow and pressure, not from the kinetic energy of the flow.A hydraulic drive system consists of three parts: The generator (e.g. a hydraulic pump), driven by an electric motor, a combustion engine or a windmill; valves, filters, piping etc. (to guide and control the system); the motor (e.g. a hydraulic motor or hydraulic cylinder) to drive the machinery.

2.1 Principle of a hydraulic drive

Pascal law is the basis of hydraulic drive systems. As the pressure in the system is the same, the force that the fluid gives to the surroundings is therefore equal to pressure x area. In such a way, a small piston feels a small force and a large piston feels a large force. The same principle applies for a hydraulic pump with a small swept volume that asks for a small torque, combined with a hydraulic motor with a large swept volume that gives a large torque. In such a way a transmission with a certain ratio can be built.Most hydraulic drive systems make use of hydraulic cylinders. Here the same principle is used- a small torque can be transmitted in to a large force.

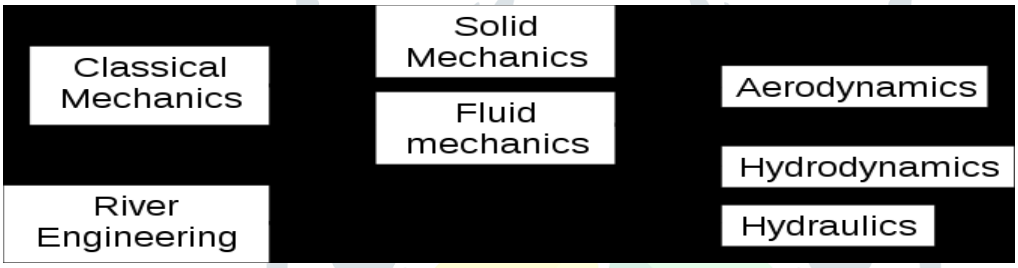
By throttling the fluid between the generator part and the motor part, or by using hydraulic pumps and/or motors with adjustable swept volume, the ratio of the transmission can be changed easily. In case throttling is used, the efficiency of the transmission is limited. In case adjustable pumps and motors are used, the efficiency, however, is very large. In fact, up to around 1980, a hydraulic drive system had hardly any competition from other adjustable drive systems.

Nowadays, electric drive systems using electric servo-motors can be controlled in an excellent way and can easily compete with rotating hydraulic drive systems. Hydraulic cylinders are, in fact, without competition for linear forces. For these cylinders, hydraulic systems will remain of interest and if such a system is available, it is easy and logical to use this system for the rotating drives of the cooling systems, also.

2.2 HYDRAULICS

Hydraulics is a topic in applied science and engineering dealing with the mechanical properties of liquids. Fluid mechanics provides the theoretical foundation for hydraulics, which focuses on the engineering uses of fluid properties. In fluid power, hydraulics is used for the generation, control, and transmission of power by the use of pressurized liquids. Hydraulic topics range through most science and engineering disciplines, and cover concepts such as pipe flow, dam design, fluidics and fluid control circuitry, pumps, turbines, hydropower, computational fluid dynamics, flow measurement, river channel behavior and erosion.

Free surface hydraulics is the branch of hydraulics dealing with free surface flow, such as occurring in rivers, canals, lakes, estuaries and seas. Its sub-field open channel flow studies the flow in open channels.



2.3 Hydraulic cylinder

Hydraulic cylinders (also called linear hydraulic motors) are mechanical actuators that are used to give a linear force through a linear stroke. Hydraulic cylinders are able to give pushing and pulling forces of millions of metric tons with only a simple hydraulic system. Very simple hydraulic cylinders are used in presses; here, the cylinder consists of a volume in a piece of iron with a plunger pushed in it and sealed with a cover. By pumping hydraulic fluid in the volume, the plunger is pushed out with a force of plunger-area pressure.

More sophisticated cylinders have a body with end cover, a piston rod, and a cylinder head. At one side the bottom is, for instance, connected to a single clevis, whereas at the other side, the piston rod is also foreseen with a single clevis. The cylinder shell normally has hydraulic connections at both sides; that is, a connection at the bottom side and a connection at the cylinder head side. If oil is pushed under the piston, the piston rod is pushed out and oil that was between the piston and the cylinder head is pushed back to the oil tank.The pushing or pulling force of a hydraulic cylinder is as follows:

$$F = Ab * pb - Ah * ph$$

F = Pushing Force in N

$Ab = (\pi/4) * (\text{Bottom-diameter})^2$ [in m2]

$Ah = (\pi/4) * ((\text{Bottom-diameter})^2-(\text{Piston-rod-diameter})^2)$ [in m2]

pb = pressure at bottom side in [N/m2]

ph = pressure at cylinder head side in [N/m2]

Apart from miniature cylinders, in general, the smallest cylinder diameter is 32 mm and the smallest piston rod diameter is 16 mm.Simple hydraulic cylinders have a maximum working pressure of about 70 bar. The next step is 140 bar, 210 bar, 320/350 bar and further. In general, the cylinders are custom built. The stroke of a hydraulic cylinder is limited by the manufacturing process. The majority of hydraulic cylinders have a stroke between 0, 3, and 5 meters, whereas 12-15 meter stroke is also possible, but for this length only a limited number of suppliers are on the market.

In case the retracted length of the cylinder is too long for the cylinder to be built in the structure, telescopic cylinders can be used. One has to realize that for simple pushing applications telescopic cylinders might be easily available; for higher forces and/or double acting cylinders, they must be designed especially and are very expensive. If hydraulic cylinders are only used for pushing and the piston rod is brought in again by other means, one can also use plunger cylinders. Plunger cylinders have no sealing over the piston, if the cylinder even exists. This means that only one oil connection is necessary. In general the diameter of the plunger is rather large compared with a normal piston cylinder, whereas a hydraulic motor will always leak oil. A hydraulic cylinder does not have a leakage over the piston nor over the cylinder head sealing so that there is no need for a mechanical brake.

Hydraulic cylinders get their power from pressurized hydraulic fluid, which is typically oil. The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on each end by the cylinder bottom (also called the cap end) and by the cylinder head where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder in two chambers, the bottom chamber (cap end) and the piston rod side chamber (rod end). The hydraulic pressure acts on the piston to do linear work and motion.

Flanges, trunnions, and/or clevisses are mounted to the cylinder body. The piston rod also has mounting attachments to connect the cylinder to the object or machine component that it is pushing.An hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings in a fixed or regulated flow of oil to the bottom side of the hydraulic cylinder, to move the piston rod upwards. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil pressure in the piston rod chamber is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A:

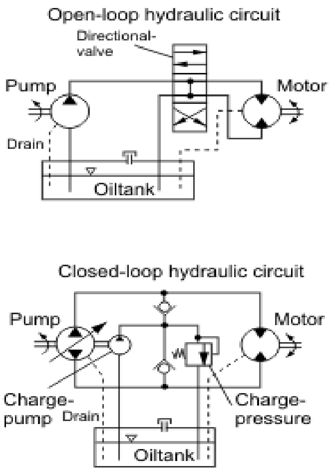
$$F = P \cdot A$$

The piston moves instead downwards if oil is pumped into the piston rod side chamber and the oil from the piston area flows back to the reservoir without pressure. The fluid pressure in the piston rod area chamber is (Pull Force) / (piston area - piston rod area):

$$P = \frac{F_p}{A_p - A_r}$$

where P is the fluid pressure, F_p is the pulling force, A_p is the piston face area and A_r is the rod cross-section area.

2.4 Hydraulic motor



Principal circuit diagram for open loop and closed loop system.

The hydraulic motor is the rotary counterpart of the hydraulic cylinder. Conceptually, a hydraulic motor should be interchangeable with the hydraulic pump, due to the fact it performs the opposite function. However, most hydraulic pumps cannot be used as hydraulic motors because they cannot be backdriven. Also, a hydraulic motor is usually designed for the working pressure at both sides of the motor. Another difference is that a motor can be reversed by a reversing valve.

Pressure in a hydraulic system is like the voltage in an electrical system and fluid flow rate is the equivalent of current. The size and speed of the pump determines the flow rate, the load at the motor determines the pressure.

2.5 Hydraulic valves

These valves are usually very heavy duty to stand up to high pressures. Some special valves can control the direction of the flow of fluid and act as a control unit for a system.

Classification of hydraulic valves

- Classification based on function:

1. Pressure control valves
2. Flow control valves
3. Direction control valves (DC Valves)

- Classification based on method of activation:

1. Directly operated valve
2. Pilot operated valve
3. Mutually operated valve
4. Electrically actuated valve
5. open control valve
6. Servo controlled valves

II. ACTUATOR

An actuator is a type of motor for moving or controlling a mechanism or system. It is operated by a source of energy, usually in the form of an electric current, hydraulic fluid pressure or pneumatic pressure, and converts that energy into some kind of motion. An actuator is the mechanism by which an agent acts upon an environment. The agent can be either an artificial intelligent agent or any other autonomous being (human, other animal, etc).

Human - Arms, hands, fingers, legs Part picking robot - Grasping mechanism, moving parts. Examples include solenoids and voice coil actuators. Mail transfer agent - Update software In engineering, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into motion. Electrical motors, pneumatic actuators, hydraulic pistons, relays, comb drive, piezoelectric actuators, thermal bimorphs, Digital Micromirror Devices and electroactive polymers are some examples of such actuators. Motors are mostly used when circular motions are needed, but can also be used for linear applications by transforming circular to linear motion with a bolt and screw transducer. On the other hand, some actuators are intrinsically linear, such as piezoelectric actuators. In virtual instrumentation actuators and sensors are the hardware complements of virtual instruments. Computer programs of virtual instruments use actuators to act upon real world objects.

- Mechanical actuators operate by conversion of rotary motion into linear motion, or vice versa. Conversion is commonly made via a few simple types of mechanism including:

    - Screw: Screw jack, ball screw and roller screw actuators all operate on the principle of the simple machine known as the screw. By rotating the actuator's nut, the screw shaft moves in a line. By moving the screw shaft, the nut rotates.

    - Wheel and axle: Hoist, winch, rack and pinion, chain drive, belt drive, rigid chain and rigid belt actuators operate on the principle of the wheel and axle. By rotating a wheel/axle (e.g. drum, gear, pulley or shaft) a linear member (e.g. cable, rack, chain or belt) moves. By moving the linear member, the wheel/axle rotates.[1]

- In engineering, actuators are frequently used as mechanisms to introduce motion, or to clamp an object so as to prevent motion. In electronic engineering, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into motion. Specific examples include: electrical motors, pneumatic actuators, hydraulic actuators, linear actuators, comb drive, piezoelectric actuators and amplified piezoelectric actuators, thermal bimorphs, micromirror devices and electroactive polymers.
- Motors are mostly used when circular motions are needed, but can also be used for linear applications by transforming circular to linear motion with a bolt and screw transducer. On the other hand, some actuators are intrinsically linear, such as piezoelectric actuators.
- "Force fighting" can occur when two or more actuators provide conflicting inputs to the mechanism

Thermodynamic efficiency

The efficiency of an actuator is a standard tool used to calculate or estimate the usefulness of any actuating mechanism. It is a dimensionless quantity which is lower than 1 expressing the energy conversion factor. For better explanation see Thermodynamic efficiency. Most of the wasted energy (due to friction, magnetic losses, eddy currents etc.) is thermally dissipated.

$$\varepsilon = \frac{\text{useful work}}{\text{spent energy}} = \frac{\text{output energy}}{\text{input energy}}$$

III. HYDRAULIC MANIPULATOR

Hydraulic manipulators are candidate for fusion reactor maintenance. Their main advantages are their large payload with respect to volume and mass, their reliability and their robustness. However, due to their force control limitations, they are disqualified for precise manipulation. For the same reason, they are dangerous for the environment and themselves in case of undesired contact or unexpected collision with the environment. CEA, in collaboration with CYBERNETIX and IFREMER has developed the advanced hydraulic robot MAESTRO Fournie, Measson, Gravez. Force and hybrid control has been developed in order to avoid these problems.

The MAESTRO arm actuating technology is based on an intensive use of "flow" control servo-valves. It means that the response of the servo valve to an electrical current step is a precise flow of oil in the joint. For force monitoring of the arm, pressure sensors are used in the control loop to set an equivalence between the pressure in the joint's chambers and the flow provided by the valve. Using «pressure» control servo-valve instead of «flow» control servo-valve makes a real simplification of the control loop. In that case the response to a current step is a pressure step and no more extra sensors are needed for monitoring the hydraulic joint in force control mode. Using this kind of valves makes also big safety improvements, for the environment and for the arm itself. The feasibility of such a control methodology was proven with existing industrial pressure servo valves on a mock-up. The french company IN-LHC, designed and manufactured a prototype of valve that fits the performances and space constraints of the Maestro arm.

The MAESTRO hydraulic manipulator is a 120kg Titan arm with six degrees of freedom. The oil is supplied through the arm at a 210bars pressure and a rate of 15l/min. It is able to carry a 70daN payload at a 2.3m distance from the axis of the first joint. The actuators technology is based on rotary hydraulic joints. Oil is sent in one of the two chambers of the actuator's cylinder and push on a paddle mounted on the rotor part of the joint. Monitoring the pressure difference in the two chambers of the actuators makes possible to drive the arm in a force control mode. It also ensures reversibility of all the actuators for their use in a force reflective master-slave system. The MAESTRO was designed to be Rad-tolerant. Its dose limit was set to 1MRad. Its large payload versus its weight and volume makes it a good candidate for maintenance work in the divertor region of ITER. Each joint is equipped with a servo-valve, which controls the in and out oil flow through the joint's chambers. The servo-valves used in the MAESTRO were of the "flow" control type. It means that for an electrical current input the response is a precise oil flow rate. This kind of valves can be used without any problem in position controlled loops, but need additional sensor information when they are used in force controlled loops. Force monitoring of the joint can only be made when a measurement of the pressure in the joint's chambers is provided.

The pressure in the chamber is used to build the corrective torque that feeds the loop and makes the arm reversible. The corrective torque is composed of a part coming from the friction compensation (dry and viscous) and a second one for gravity compensation. Accurate modelling of the corrective torque and high accuracy of the pressure sensors are necessary to provide a good reflection of the force in the operator's arm in master-slave mode.

IV. CONTROL SYSTEM

A control system is a device, or set of devices to manage, command, direct or regulate the behavior of other devices or system.There are two common classes of control systems, with many variations and combinations: logic or sequential controls, and feedback or linear controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable

The term "control system" may be applied to the essentially manual controls that allow an operator, for example, to close and open a hydraulic press, perhaps including logic so that it cannot be moved unless safety guards are in place.

An automatic sequential control system may trigger a series of mechanical actuators in the correct sequence to perform a task. For example various electric and pneumatic transducers may fold and glue a cardboard box, fill it with product and then seal it in an automatic packaging machine.

In the case of linear feedback systems, a control loop, including sensors, control algorithms and actuators, is arranged in such a fashion as to try to regulate a variable at a setpoint or reference value. An example of this may increase the fuel supply to a furnace when a measured temperature drops. PID controllers are common and effective in cases such as this. Control systems that include some sensing of the results they are trying to achieve are making use of feedback and so can, to some extent, adapt to varying circumstances. Open-loop control systems do not make use of feedback, and run only in pre-arranged ways.

Logic control systems for industrial and commercial machinery were historically implemented at mains voltage using interconnected relays, designed using ladder logic. Today, most such systems are constructed with programmable logic controllers (PLCs) or microcontrollers. The notation of ladder logic is still in use as a programming idiom for PLCs.Logic controllers may respond to switches, light sensors, pressure switches, etc., and can cause the machinery to start and stop various operations. Logic systems are used to sequence mechanical operations in many applications. Examples include elevators, washing machines and other systems with interrelated stop-go operations.

Logic systems are quite easy to design, and can handle very complex operations. Some aspects of logic system design make use of Boolean logic.

5.1 On–off control

For more details on this topic, see Bang–bang control.

For example, a thermostat is a simple negative-feedback control: when the temperature (the "process variable" or PV) goes below a set point (SP), the heater is switched on. Another example could be a pressure switch on an air compressor: when the pressure (PV) drops below the threshold (SP), the pump is powered. Refrigerators and vacuum pumps contain similar mechanisms operating in reverse, but still providing negative feedback to correct errors.

Simple on–off feedback control systems like these are cheap and effective. In some cases, like the simple compressor example, they may represent a good design choice.

In most applications of on–off feedback control, some consideration needs to be given to other costs, such as wear and tear of control valves and maybe other start-up costs when power is reapplied each time the PV drops. Therefore, practical on–off control systems are designed to include hysteresis, usually in the form of a deadband, a region around the setpoint value in which no control action occurs. The width of deadband may be adjustable or programmable.

5.2 Linear control

Linear control systems use linear negative feedback to produce a control signal mathematically based on other variables, with a view to maintaining the controlled process within an acceptable operating range.

The output from a linear control system into the controlled process may be in the form of a directly variable signal, such as a valve that may be 0 or 100% open or anywhere in between. Sometimes this is not feasible and so, after calculating the current required corrective signal, a linear control system may repeatedly switch an actuator, such as a pump, motor or heater, fully on and then fully off again, regulating the duty cycle using pulse-width modulation.

5.3 Proportional control

When controlling the temperature of an industrial furnace, it is usually better to control the opening of the fuel valve in proportion to the current needs of the furnace. This helps avoid thermal shocks and applies heat more effectively.

Proportional negative-feedback systems are based on the difference between the required set point (SP) and process value (PV). This difference is called the error. Power is applied in direct proportion to the current measured error, in the correct sense so as to tend to reduce the error (and so avoid positive feedback). The amount of corrective action that is applied for a given error is set by the gain or sensitivity of the control system.

At low gains, only a small corrective action is applied when errors are detected: the system may be safe and stable, but may be sluggish in response to changing conditions; errors will remain uncorrected for relatively long periods of time: it is over-damped. If the proportional gain is increased, such systems become more responsive and errors are dealt with more quickly. There is an optimal value for the gain setting when the overall system is said to be critically damped. Increases in loop gain beyond this point will lead to oscillations in the PV; such a system is under-damped.

5.4 PI controller

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative (D) of the error is not used.The controller output is given by

$$K_P\Delta + K_I \int \Delta\, dt$$

where Δ is the error or deviation of actual measured value (PV) from the set-point (SP).

$$\Delta = SP - PV.$$

A PI controller can be modelled easily in software such as Simulink using a "flow chart" box involving Laplace operators:

$$C = \frac{G(1+\tau s)}{\tau s}$$

where

$G = K_P$ = proportional gain
$G / \tau = K_I$ = integral gain

Setting a value for G is often a trade off between decreasing overshoot and increasing settling time.

The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs.Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach setpoint and slower to respond to perturbations than a well-tuned PID system may be.

5.5 PID control

Apart from sluggish performance to avoid oscillations, another problem with proportional-only control is that power application is always in direct proportion to the error. In the example above we assumed that the set temperature could be maintained with 50% power. What happens if the furnace is required in a different application where a higher set temperature will require 80% power to maintain it? If the gain was finally set to a 50° PB, then 80% power will not be applied unless the furnace is 15° below setpoint, so for this other application the operators will have to remember always to set the setpoint temperature 15° higher than actually needed. This 15° figure is not completely constant either: it will depend on the surrounding ambient temperature, as well as other factors that affect heat loss from or absorption within the furnace.

To resolve these two problems, many feedback control schemes include mathematical extensions to improve performance. The most common extensions lead to proportional-integral-derivative control, or PID control (pronounced pee-eye-dee).

V. INTEGRATED DIRECT/INDIRECT ADAPTIVE ROBUST CONTROL

The following nomenclature is used throughout this paper:
• is used to denote the estimate of •, • is used to denote the estimation error of •, e.g., θ = θ − θ. Since the extents of the parametric uncertainties and uncertain nonlinearities are normally known, the following practical assumptions are made.

The unknown parameter vector θ lies within a known bounded-convex set Ωθ . Without loss of generality, it is assumed that ∀θ ∈ Ωθ , θimin ≤ θi ≤ θimax , i =1,..., 9, where θimin and θimax are some known constants, respectively.
Assumption 2: All the uncertain nonlinearities are bounded, i.e., Di ∈ Ωd = { D : | D|≤ δi ,i =1, 21, 22}, where δi (t) is a known bounded function.

Assumption 3: The actual valve-orifice opening xn is not measured.

Projection-Type Adaptation Law With Rate Limits

One of the key elements of the DIARC design is to use the practical available a prior information to construct the projection-type adaptation law for a controlled learning process.
For this purpose, we define the following projection mapping

$$\mathrm{Proj}_{\hat{\theta}}(\zeta) = \begin{cases} \zeta, & \hat{\theta} \in \overline{\Omega}_{\theta} \text{ or } n_{\hat{\theta}}^{T}\zeta \le 0 \\ \left(I - \Gamma \dfrac{n_{\hat{\theta}} n_{\hat{\theta}}^{T}}{n_{\hat{\theta}}^{T} \Gamma n_{\hat{\theta}}} \right) \zeta, & \hat{\theta} \in \partial\Omega_{\theta} \ \& \ n_{\hat{\theta}}^{T}\zeta > 0 \end{cases}$$

where ζ ∈ Rp and Γ(t) ∈ Rp×p are any time-varying positive definite-symmetric matrix, Ωθ and ∂Ωθ denote the interior and the boundary of Ωθ , respectively, and nˆ θ represents the outward unit normal vector at θ ∈ ∂Ωθ .

We also define the following saturation function sat ˙ (•)

$$\mathrm{sat}_{\dot{\theta}_M}(\zeta) = s_0 \zeta, \quad s_0 = \begin{cases} 1, & \|\zeta\| \le \dot{\theta}_M \\ \dfrac{\dot{\theta}_M}{\|\zeta\|}, & \|\zeta\| > \dot{\theta}_M . \end{cases}$$

Lemma 1 ([7], [9]): Suppose that the parameter estimate θ is updated using the following parameter estimator structure:

$$\dot{\hat{\theta}} = \mathrm{sat}_{\dot{\theta}_M}\left(\mathrm{Proj}_{\hat{\theta}}(\Gamma\tau)\right), \quad \hat{\theta}(0) \in \Omega_{\theta}$$

where Γ=ΓT > 0 is the adaptive-rate matrix and τ is the adaptation function (both of them to be designed later). With this adaptation-law structure, the following desirable properties hold:

P1: The parameter estimates are always within the known bounded set Ωθ , i.e., θ(t) ∈ Ωθ , ∀t. Thus, from Assumption 1, θimin ≤ θi (t) ≤ θimax , i =1,..., 9 ∀t.
P2: θTΓ−1Proj θ(Γτ) − τ≤ 0 ∀τ .
P3: The parameter update rate θ is uniformly bounded by

θ(t)≤ ˙ θM ∀t.

6.1 DIARC-Control Law

As pointed out in Lemma 1, with the use of projection-type adaptation law with rate limit (16), the parameter estimates and their derivatives are bounded with known bounds, regardless of how the actual estimation function τ and adaptation-rate matrix Γ are designed. In this section, this property will be utilized to synthesize a robust-control law for the system that achieves a guaranteed transient and final tracking error independent of the parameter-estimator design.
As the system (9)–(12) has unmatched model uncertainties, back-stepping design is used as follows:

Step 1: Define a variable z2 as

$$z_2 = \dot{z}_1 + k_1 z_1 = x_2 - x_{2\mathrm{eq}}, \quad x_{2\mathrm{eq}} \overset{\triangle}{=} \dot{x}_{1d} - k_1 z_1$$

where z1 = x1 − qd (t) is the output tracking error and k1 is any positive feedback gain. Since Gs (s)= z1 (s)/z2 (s)=1/(s + k1) is a stable-transfer function,making z2 small or converging to zero is equivalent to making z1 small or converging to zero. Differentiating (17) and noting (10), we obtain

$$\theta_1 \dot{z}_2 = \mu(x_3 - x_4) - \theta_2 x_2 - \theta_3 S(x_2) + \theta_4 - \theta_1 \dot{x}_{2\mathrm{eq}} + \tilde{D}_1.$$

Define the actuator load as FL = x3 − x4 . In (18), treating FL as the virtual control, the following virtual DIARC law α2 for FL is designed

$$\alpha_2 = \alpha_{2a} + \alpha_{2s} = \alpha_{2a1} + \alpha_{2a2} + \alpha_{2s1} + \alpha_{2s2}$$

$$\alpha_{2a1} = \mu^{-1}[\hat{\theta}_1 \dot{x}_{2\mathrm{eq}} + \hat{\theta}_2 x_2 + \hat{\theta}_3 S(x_2) - \hat{\theta}_4]$$

$$\alpha_{2s1} = -\mu^{-1} k_{2s1} z_2, \alpha_{2s2} = -\mu^{-1} k_{2s2}(x_1, x_2, t) z_2.$$

6.2 Non-linear Neural Network Control

The term neural network was traditionally used to refer to a network or circuit of biological neurons. The modern usage of the term often refers to artificial neural networks, which are composed of artificial neurons or nodes. Thus the term has two distinct usages:

1. Biological neural networks are made up of real biological neurons that are connected or functionally related in a nervous system. In the field of neuroscience, they are often identified as groups of neurons that perform a specific physiological function in laboratory analysis.
2. Artificial neural networks are composed of interconnecting artificial neurons (programming constructs that mimic the properties of biological neurons). Artificial neural networks may either be used to gain an understanding of biological neural networks, or for solving artificial intelligence problems without necessarily creating a model of a real biological system. The real, biological nervous system is highly complex: artificial neural network algorithms attempt to abstract this complexity and focus on what may hypothetically matter most from an information processing point of view. Good performance (e.g. as measured by good predictive ability, low generalization error), or performance mimicking animal or human error patterns, can then be used as one source of evidence towards supporting the hypothesis that the abstraction really captured something important from the point of view of information processing in the brain. Another incentive for these abstractions is to reduce the amount of computation required to simulate artificial neural networks, so as to allow one to experiment with larger networks and train them on larger data sets.

This article focuses on the relationship between the two concepts; for detailed coverage of the two different concepts refer to the separate articles: biological neural network and artificial neural network.

A biological neural network is composed of a group or groups of chemically connected or functionally associated neurons. A single neuron may be connected to many other neurons and the total number of neurons and connections in a network may be extensive. Connections, called synapses, are usually formed from axons to dendrites, though dendrodendritic microcircuits and other connections are possible. Apart from the electrical signaling, there are other forms of signaling that arise from neurotransmitter diffusion, which have an effect on electrical signaling. As such, neural networks are extremely complex.

Artificial intelligence and cognitive modeling try to simulate some properties of biological neural networks. While similar in their techniques, the former has the aim of solving particular tasks, while the latter aims to build mathematical models of biological neural systems.In the artificial intelligence field, artificial neural networks have been applied successfully to speech recognition, image analysis and adaptive control, in order to construct software agents (in computer and video games) or autonomous robots. Most of the currently employed artificial neural networks for artificial intelligence are based on statistical estimations, Classification optimization and control theory.

The cognitive modelling field involves the physical or mathematical modeling of the behavior of neural systems; ranging from the individual neural level (e.g. modelling the spike response curves of neurons to a stimulus), through the neural cluster level (e.g. modelling the release and effects of dopamine in the basal ganglia) to the complete organism (e.g. behavioral modelling of the organism's response to stimuli). Artificial intelligence, cognitive modelling, and neural networks are information processing paradigms inspired by the way biological neural systems process data.

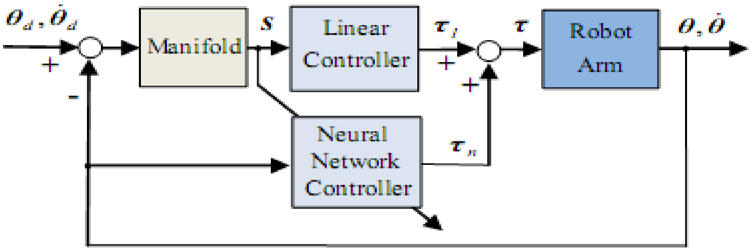
Neural network control systen design
Structure of the Control System

For tracking planned joint trajectories, we design a manifold to describe the desired tracking performance of the robot as

$$s = 0 \qquad (2)$$

$$\text{where } s = \dot{e} + \lambda e \text{ , } e = \theta - \theta_d \text{ , and } \dot{e} = \dot{\theta} - \dot{\theta}_d \text{ ; } \theta_d$$

, and d θ θ e □ □ □ □ □; d θand d θ □ are the planned joint trajectories, n nR □□ λis a selected positive constant matrix. Control system is designed with a linear feedback controller and two neural network controllers. The structure of the control system is shown in Figure



The Control Scheme
The control scheme is given as follows.

$$\tau = \tau_l + \tau_n$$

τ_l is control input of the linear controller, and can be simply described as below.

$$\tau_l = -Ks$$

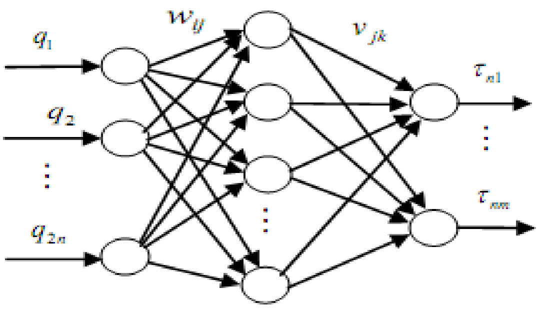
where $K \in R^{n \times n}$ is a positive-definite gain matrix.

τ_n is a positive-definite gain matrix. n τ is the control input generated by the neural network control to be designed.The structure of neural network controller is shown in Figure 2. The detail mathematical description of the neural network is given by

$$\tau_n = V f(Wq)$$

where

$$q = [\theta_1, \theta_2, \cdots \theta_n, \dot{\theta}_1, \dot{\theta}_2, \cdots \dot{\theta}_n]^T \in R^{2n}$$



denotes input vector with elements being each joint

variable, velocity; $\tau_n = [\tau_{n1}, \tau_{n2} \cdots \tau_{nm}] \in R^m$ is output vector $W \in R^{2n \times l}$ and $V \in R^{l \times m}$ with their elements being expressed by ijwand jk v

, are weight matrices from input nodes to the hidden layer and from hidden layer to the output layer; $f(*) \in R^l$ is an activation function vector of the hidden layer with elements being selected as a saturation function, such as a sigmoid function; l is the number of hidden nodes.

Though the dimension of robot joint inputs equals joint numbers n, here we denote it as m, i.e. m=n in order to describe the network controller design without confusion. In this research, we select the activation function vector with its individual element being a hyperbolic function as follows.

$$f_j(z_j) = \frac{e^{z_j} - e^{-z_j}}{e^{z_j} + e^{-z_j}} \quad (j = 1,2,\cdots l)$$

where jz is the summation of input signals to jth node of the hidden layer and can be given as

$$z_j = [w_{1j}\ w_{2j} \cdots w_{2n\,j}] \cdot \boldsymbol{q}$$

VI. CONCLUSION

DIARC was proposed for high-performance-motion control of an electro-hydraulic systems driven by single-rod actuators with input valve deadband. The proposed con-troller uses least-squares type indirect parameter adaptation al-gorithm with certain condition monitoring to estimate accurate deadband parameters. Furthermore, a fast dynamic compensa-tion similar to the DARC design is employed to improve the tracking performance. Experimental results are presented to il-lustrate the effectiveness of the proposed algorithm.

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