Unknown and Time-Varying Time Delays in the Modelling and Control of Hydraulic Actuators: Literature Review

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***Abstract*—Uncertain time-delays can reduce the performance of hydraulic manipulator control systems. Variations in the time delay between, for example, an applied voltage and the associated manipulator movement, may be caused by the internal dynamics of the system and other nonlinear characteristics, such as fluid compressibility, dead-band of the pump, valve flow properties and friction characteristics. Robot control that addresses system time-delays, nonlinearities and uncertainty is the subject of much research but, whilst the specific concept of varying time delays in hydraulic systems is sometimes acknowledged, it appears to be less widely investigated than other types of uncertainty. The present article discuses some of the issues involved, exemplified by a dual manipulator device used in the laboratory for research into nuclear decommissioning, and presents a review of the relevant control literature in this area.**

***Index Terms*—hydraulic manipulators, uncertain time delays, time varying delays, robot control systems, literature review**

I. Introduction

This article concerns the modelling and control of hydraulically actuated robotic manipulators that are subject to uncertain and potentially time-varying time-delays. This refers, for example, to the time-delay in seconds between changing an applied voltage (in open or closed-loop scenarios) and observing a corresponding change in the manipulator movement characteristics i.e. direction of movement or angular velocity. As discussed later, such delays may be caused by the internal dynamics of the system and are influenced by nonlinear characteristics, including fluid compressibility, dead-band of the pump, valve flow properties and friction characteristics, among other mechanical, electrical and software issues [1].

From a modelling and control systems design perspective, these challenges are well exemplified by the dual–HYDROLEK manipulators used by the present authors for research into nuclear decommissioning [2], [3], [4], [5]. Many nuclear facilities around the world have reached the end of their useful life. Since it is environmentally unfriendly and dangerous for plant workers, decommissioning tasks are accomplished with robots where possible, for which direct tele-operation is currently standard practice [6]. With constrained spaces and highly-contaminated facilities, fully autonomous solutions are unlikely to be considered safe or cost-effective in the near future. Nonetheless, with the advent of efficient and robust embedded electronics and sensors, there is significant interest in semi-autonomous capabilities [4], [7].

The robotic platform used for experimental work in the present study has dual, seven-function, hydraulically actuated manipulators, for which the authors are investigating use of vision-based interfaces for common nuclear decommissioning tasks, such as pipe cutting. It is clear that, to improve safety, task execution speed and operator training-time, high performance control of the nonlinear manipulator dynamics is also required, necessitating the identification of suitable models and control algorithms. Hence, one aspect of the research programme concerns the development of improved 'low-level' control systems, such that the 'higher-level' task orientated objectives are achieved more effectively.

Hydraulic models and control systems are the subject of much theoretical and applied research [1]. However, it is notable that uncertainties and nonlinearities, including actuator deadbands and time-delays, are not always fully addressed in the literature [8]. In fact, two major challenges in high performance positioning and tracking stabilisation of manipulators, are the friction between moving parts and the deadband of the actuators, which are both sometimes linked to observed time delays. Furthermore, whilst the concept of uncertain and varying time delays is occasionally acknowledged [9], this specific issue appears to be even less widely discussed.

The present article utilises a laboratory example to highlight some of the research challenges (sections II and III) and presents a necessarily subjective review of the relevant literature. The literature review is illustrative rather than complete but aims to consider both hydraulic manipulator control (section IV) and, in more general terms, methods from the control domain for potentially dealing with the identified time-varying delays (section V). Finally, additional discussion and the conclusions are presented in sections VI and VII.

II. Laboratory Example

The laboratory system consists of two HYDROLEK HLK-7W manipulators, each a 6-degrees-of-freedom (6-DOF) articulated arm, with a seventh actuator for the gripper, as

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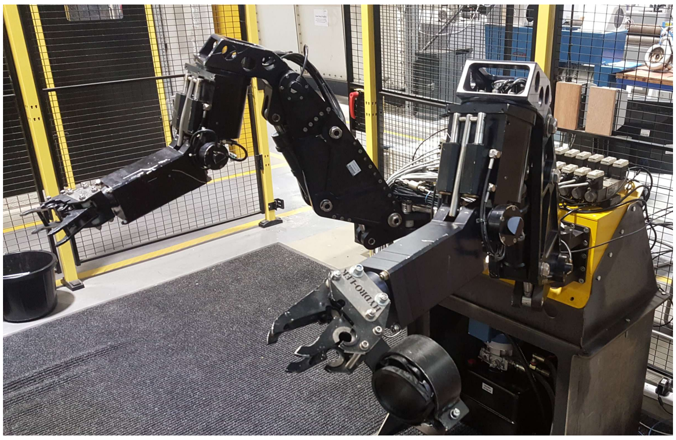

Fig. 1. HYDROLEK HLK-7W manipulators in the laboratory.

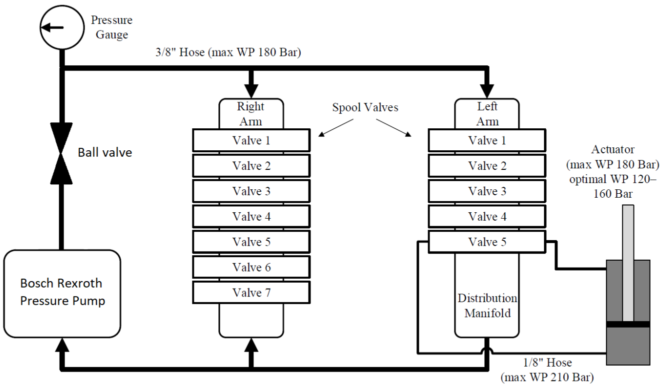

Fig. 2. Schematic diagram of the reconfigured hydraulic system.

illustrated by Fig. 1. In comparison to earlier publications, the system has been reconfigured, hence the new hardware framework and control software are very briefly described below. Photos are available at: http://wp.lancs.ac.uk/cjtaylor/brokk/

Whilst the original set-up is described by reference [4], a ball valve, pressure gauge and new pressure pump were added in 2019. Fig. 2 shows the location of these new elements. The hydraulic system was upgraded with a Bosch Rexroth Pressure & Tank Circuit Hydraulic Power Unit, providing 5.5 L/min at 220 bar and has a 15 L oil tank.

The manipulators are now controlled via a NI Compact DAQ 9132 system. The cDAQ 9132 is a 1.33 GHz Dual-core atom computer with 4 slots for I/O modules. The system runs both Windows 7 Embedded Edition and Labview 2018 for programming and interfacing. The cDAQ 9132 utilises three I/O modules: one NI 9205 i.e. a 32-channel analogue-to-digital (ADC) converter and two NI 9264 i.e. 16-channel digital-to-analogue converters (DAC). The two NI 9264 modules are used to actuate the P02AD1 valves in the two manipulators. The position angle sensors are rotary linear potentiometers.

A dedicated box is installed next to the robot in order to hold the controller and associated equipment. A monitor, mouse and keyboard are externally connected such that an operator can control or program the robot from outside the safety cell (to some degree, representing the situation on a nuclear site where the robot will be remote from the operator). Since the present article focuses on the low-level joint control problem, inverse kinematics and the human-machine interface are not described here: see [4] for a recent reference.

To illustrate the time delay issue, consider the following simplified, first order model for each manipulator joint,

$$\dot{\theta}(t) = -a_1\theta(t) + b_1 u(t-\tau) \tag{1}$$

with a_1, b_1 and the time-delay τ estimated from open-loop experimental data using the SRIVC algorithm [10] in the CAPTAIN toolbox [11]. Here, $u(t)$ and $\theta(t)$ represent the control input and joint angle respectively, where the former is a scaled signal in the range ± 10. Further analysis of experimental data, suggests that $a_1 \approx 0$ is time invariant, whilst b_1 is a State Dependent Parameter (SDP), hence,

$$\dot{\theta}(t) = q\left\{u(t-\tau)\right\} \tag{2}$$

where $q\left\{u(t-\tau)\right\}$ represents a static nonlinear function of the input [5]. For brevity, further details are omitted from this article, but see [2] or [4] for an example of this static nonlinearity. Equations (1) and (2) assume time–invariant τ. However, even for a rather straightforward sequence of step experiments, considering one joint in isolation, significant variation in the time-delay can be observed, as shown by Fig. 3. In fact, for the HYDROLEK manipulators, this delay typically ranges from almost zero to over 1.2 s.

The present first author is developing a novel binomial regression optimisation approach for the estimation of time-delay variations from experimental data. The algorithm is being utilised to determine suitable state-dependencies for the design of new SDP controllers. For example, Fig. 4 shows how the estimated time delay varies with the average angular velocity i.e. as estimated just before and after a change in the input signal (further research is required). In this context, a more general SDP model might take the following form,

$$\dot{\theta}(t) = q\left\{u(t-\tau(t))\right\} \tag{3}$$

Although not the focus of the present work, the new estimation algorithm shows how the delay can vary both from experiment to experiment (as for the case of Fig. 3) or during the normal operation of the machine (as implied by equation (3)), hence introducing a substantial challenge for control system design.

III. Sources of Time-Varying Time Delays

The concept of uncertain time delays in hydraulic systems does not seem to be widely discussed, however is acknowledged directly by Magyar et al. [9]. Their hydraulic system consists of a differential hydraulic cylinder, a proportional directional valve, a gear pump and a linear potentiometer that is used to send a signal to the PC to indicate the position of the actuator. The overall time delay of the system response consists of two parts: the first is a delay caused by the computation of the error signal based on the position signal,

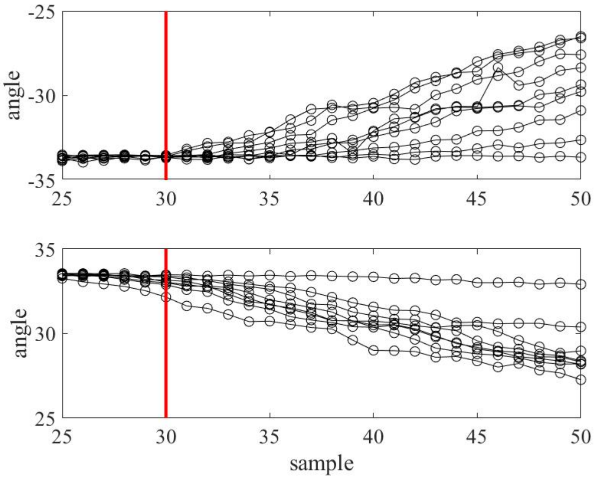

Fig. 3. Open–loop step experiments for the HYDROLEK shoulder joint for a range of input magnitudes, with the time-delay of the linear model shown as a solid vertical line (i.e. sample 30). These graphs show the observed time-delays ranges from 18 to 29 samples ($\Delta t = 10$ ms). The upper and lower subplots show the manipulator being raised and lowered respectively, with each trace representing a different experiment.

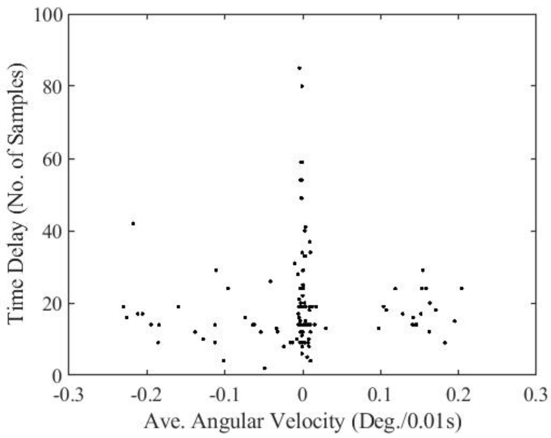

Fig. 4. Sampled time delay ($\Delta t = 10$ ms) plotted against angular velocity.

and the other is a delay caused by internal pressure dynamics of the system, which result in variations in the velocity through the valves. Significantly, the delays associated with the latter are present in open-loop experimentation [9].

For the remote control system researched by Pan et al. [12], the varying time delay is similarly understood to be dependant on two different elements: one aspect of the time delay is time-invariant and is equal to a multiple of the sampling time; the other is representated as a random variable, but (unlike for the present article) is limited to the length of the sampling rate.

More generally, hydraulic systems carry a multitude of nonlinear characteristics, as described by [13] and [14], and many other authors. These include fluid compressibility, flow properties of hydraulic valves, and friction characteristics in the actuators. Such systems yield non-smooth and discontinuous characteristics due to the dead-band of the pump and the directional change of the pump and valves. Furthermore, the compression of fluid can be due to entrained air, which suggests an entrapment of air in hydraulic oil; mechanical compliance, which suggests that any mechanical components, such as valves, can be undergoing elastic deformation as the equipment ages; and pressure and temperature changes [14].

The flow properties depend on pressure losses across valves and any transient or turbulent flow through them, and friction characteristics occur due to the properties of static, coulomb, viscous and slip-stick friction [14]. As the HYDROLEK manipulators used by the present authors have aged, their components are likely to have been subject to various stresses and strains. Since hydraulic manipulators are being researched for the purpose of providing long-lasting, durable equipment, this is an important consideration.

IV. Control of Hydraulic Manipulators

Conventional identification methods for robotic systems include maximum likelihood [15], the extended Kalman filter [16], inverse dynamic identification model with least squares (IDIM-LS; [17]) and frequency domain methods [18], among others. Instrumental variable and Refined Instrumental Variable (RIV) algorithms have also been used for modelling robotic systems, sometimes in combination with SDP (as in section II and the prior work cited) or inverse dynamic models [19]. Such models have been identified and successfully used for control of a KOMATSU hydraulic excavator [20], a BROKK–HYDROLEK hydraulic manipulator [2] and a TX40 industrial robot [21]. The HYDROLEK manipulators have also been represented using physically-based (mechanistic) equations [3], while Semini et al. [22] model their hydraulically actuated quadruped robot as a rigid body. Various software packages are available to support such modelling e.g. [22] use the Simulation Laboratory (SL) [23].

In comparison to a typical machine driven by electric motors, hydraulic actuators generally have higher loop gains, wider bandwidths and lightly-damped, nonlinear dynamics [24]. Many different controllers have been used for hydraulic systems in industry and academia. A thorough literature review is presented by Mattila et al. [1]. For example, Kotzev et al. [25] use Generalized Predictive Control (GPC) for hydraulic actuators i.e. to generate optimized inputs based on predictions of future outputs. In principle, a linear design approach such as GPC can be applied to non minimum-phase plants, open loop unstable plants, plants with badly damped poles, plants with variable or unknown time delay, and plants with unknown order, but the latter aspects do not seem to have been fully investigated for hydraulic systems.

However, positioning controllers conventionally used for hydraulic systems sometimes lack high precision due to the use of linear approximations (as discussed by [9], [14]), hence nonlinear methods are also commonly reported in the literature, especially backstepping methods [24]. In their literature review, Dwivedy et al. [26] discuss a range of both linear and nonlinear model-based control schemes for manipulators, including model reference, adaptive control, self-tuning control, feed-forward control and PID control.

Hsia et al. [27] design a Proportional-Derivative (PD) controller for an industrial hydraulic robotic manipulator. By modelling a disturbance torque, they are able to represent coupling dynamics, friction, and gravity loading of the system, allowing for prediction of potential nonlinearities. Although lead-lag controllers are predominantly used for hydraulic manipulation in industry, relatively few investigations of such controllers (as applied to hydraulic manipulators) appear in the academic literature. It is clear that the time delay variations observed in open-loop can cause significance performance degradation in the closed-loop situation, motivating the present research.

Lin [14] considers discrete-time, linear H_2 optimal control and H_∞ based PI feed-forward control for hydraulic manipulators. However, the linear model utilised for H_2 design does not directly consider any uncertainties or nonlinear characteristics, and was developed using a frequency domain model identification technique. Motivated by control inaccuracies, the thesis emphasizes the need to address nonlinearities in modelling and control design for high-precision applications.

Wang et al. [13] and Lin [14] allude to Sliding Mode Control (SMC), adaptive control, adaptive robust control and fuzzy logic control. These references show that such methods require more detailed models and tuning, and do not always perform as well the Time Delay Controller (TDC) for hydraulic manipulators. Indeed, TDC or a Time Delay Estimation (TDE) approach have been used and tested for many robotic systems, including: [13], [28], [29], [30], [31], [32], [33], [34]. It should be pointed out that not all these references concern hydraulic systems. For example, Lee et al. [31] research an unmanned aerial vehicle whose actuation systems include DC motors and linear actuators.

Wang et al. [13] design and implement a discrete-time TDC for a hydraulic manipulator system with a TDE stage, which aims to cancel out the lumped dynamics, as well as a linear PD controller to achieve tracking performance. Although one of the benefits of the TDC controller is that a model is not needed to explicitly tune the controller, a model structure is nonetheless required to determine the control law. These calculations incorporate the dynamics of the servo-valve, flow rates, pressure dynamics and torque, however, neglect the effect of oil leakage and oil compressibility on pressure dynamics [13]. The controller block diagram also includes a compensator to deal with the dead-band of each valve and an anti-windup scheme, which strengthens the tracking performance. Robustness against unknown lumped uncertainties was tested by varying the payload on the end effector. The experiments show promising results i.e. that the controller has good robustness against these uncertainties, which suggests that it may also be robust against uncertain time delays, although this is not explicitly investigated [13].

In a similar manner to [13], a command filter is used with the TDC approach of reference [31]. In the latter case, it acts to mitigate the effects of a phase delay by restoring the distorted set point. The TDC is designed to estimate and cancel load variations, achieved with the use of a time delayed signal. It may be possible to design a TDC for the HYDROLEK manipulators, as the dynamics of the system have been modelled by [3], whilst other sources, such as [35], provide further insight into the dynamic modelling of hydraulic components. However, this requires further research.

V. Control of Time-Varying Delays

This section looks beyond manipulators for generic methods of dealing with time-varying delays. Ben Atia et al. [36] introduce a method of dealing with uncertain time delays, based on an internal multi-model scheme that operates by allowing partial controllers to regulate different elements of the system. The time delay is estimated by minimizing a performance index related to the error between the model output and the true system output. Multiple model outputs are calculated for the range of possible time delays. The model output which is closest to the measured system output predicts the time delay at the given sample. This work builds on reference [37] which considers primarily linear systems with a limited variable time delay.

Zhao et al. [38] develop a method of modeling time delay time-variance via a Markov chain model, using an expectation-maximization algorithm to estimate the parameters. They consider an industrial process identification problem, where the time delay can change at every sampling instant. Ma et al. [39] introduce a variational Bayesian inference approach to model and control a system with time-varying delays. The time delay is estimated at each sample as a random variable. There are relatively few results concerning the adaptive control of continuous-time nonlinear systems with unknown time delay. Ren et al. [40], for example, point out that most existing Artificial Neural Network (ANN) strategies are suitable for nonlinear systems free from time delay or with a known delay. Huang and Lewis [41] design an ANN Predictive controller for a nonlinear tele-operated system with a time-delay that exists in feedback due to communication channels.

Reference [42] provides a stability analysis of otherwise linear systems that have time-varying delays. Huang [43] similarly focuses on the stability and performance analysis of uncertain time-delay systems, but does not explicitly address time-varying delays. A related work is by Chen and Fong [44], who consider time-varying state delays. Dawson et al. [45] propose a fuzzy logic controller which handles unknown or variable time delays for a linear tank temperature system.

The ubiquitous Smith Predictor has been used for nonlinear control of systems with variable time delay. Sbarciog et al. [46] show that decoupling system dynamics from the variable time delay leads to a Smith Predictor-like control structure, allowing for robust operation of the controller while utilizing time-invariant control parameters. Research by the present second author [47] into (linear) proportional-integral-plus (PIP) and nonlinear SDP control systems has addressed known (and time-invariant) time-delays. Limited simulation-only research has suggested that a forward path PIP control structure that encompasses a Smith Predictor, may yield improved robustness to time delay uncertainty [48] but new research is required to develop these empirical results.

Finally, in addition to the above focus on control design, various methods exist for the *estimation* of time-varying parameters and potentially uncertain time delays, including: [49], [50], [51]. For example, Tan [52] uses an ANN to construct a time-delay estimator to track the time-varying delay.

VI. Discussion

This article has considered time delays in both open and closed-loop hydraulic systems, and has illustrated with a laboratory example, how time delay variation can occur in open-loop hydraulic systems, resulting from the inherent physical characteristics, and hence lead to observed nonlinear dynamics. The literature shows that simplification of hydraulic systems via the exclusion of such nonlinearities, model uncertainties and disturbances can lead to poor control performance. This highlights the need to include these nonlinearities within the model, in order to obtain higher precision in the output of the controller [14]. Though most controllers used for hydraulic systems do not explicitly consider varying time delay, many do consider relevant methods for dealing with uncertainties in more general terms. For example, Wang et al. [13] utilise a compensator and an anti-windup scheme to handle the dead-band and improve precision. It seems likely that further improvements can be obtained by explicitly incorporating the varying-time delay into the nonlinear controller.

The multi-model controller [36] appears particularly promising in this context, although it has not, to the authors knowledge been applied to hydraulic systems to date, nor indeed to a system as complex as the dual-HYDROLEK manipulators discussed in section II. Hsia et al. [27] suggest dealing with the complexity of a manipulator by controlling the joints individually, which is how these controllers could be extended to robotic systems. The set points for the proposed multi-model controllers would be determined by calculating the inverse kinematics for a desired end-effector position.

The multi-model controller involves estimating separate linearised models for individual operating ranges. This can be applied to a single joint by estimating a model for (i) the operating zone of the dead-band, (ii) the range of input values for which the angular velocity increases on either side of the dead band limits, and (iii) for the range of input values where the angular velocity has reached saturation [4]. On the basis of the above literature review, the present authors propose combining these using the multi-model approach [36].

An alternative cascade method similarly merits further investigation. Reference [53] describes a cascade controller, which utilizes two controllers in series for a steam-fed water heater. In a hydraulic system, the coordinates of the end effector form the key output of the system, with inverse kinematics used to calculate the necessary position of the individual joints to achieve these coordinates. A voltage is applied to the valve of each joint, which determines the flow rate of hydraulic oil. The flow rate of oil subsequently sets the speed at which the joint moves. To implement a cascade controller in this context, the flow rate of hydraulic oil would be measured. The first controller determines the flow rate necessary to achieve the required angular velocity or position, and the second controller in the cascade could use the oil flow rate to determine the valve voltage. A cascade controller with this physical set-up could potentially mitigate the effects of time delay and the aforementioned nonlinear friction characteristics. However, such an approach would require the installation of new sensors, which may not be desirable for the irradiated environments of the present authors nuclear decommissioning application.

VII. Conclusions

Prior research has identified uncertain and time-varying time-delays as one of the challenges in obtaining high performance control of hydraulic manipulators, including those used for research into nuclear decommissioning [4]. Although the literature review in the present article exemplifies the wide range of control systems that have been applied to hydraulic manipulators, relatively few of these directly address the time-delay issue. However, looking beyond robotic applications, there are various examples of control theory research in this area, hence there is an opportunity to exploit such methods in the present context. This is the focus of the authors on-going research, and these results will be reported in future articles.

References

[1] J. Mattila, J. Koivumaki, D. G. Caldwell, and C. Semini, "A survey on control of hydraulic robotic manipulators with projection to future trends," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 2, pp. 669–680, 2017.

[2] C. J. Taylor and D. Robertson, "State–dependent control of a hydraulically–actuated nuclear decommissioning robot," *Control Engineering Practice*, vol. 21, no. 12, pp. 1716–1725, 2013.

[3] A. Montazeri, C. West, S. Monk, and C. J. Taylor, "Dynamic modeling and parameter estimation of a hydraulic robot manipulator using a multi–objective genetic algorithm," *International Journal of Control*, vol. 90, no. 4, pp. 661–683, 2017.

[4] M. Bandala, C. West, S. Monk, A. Montazeri, and C. J. Taylor, "Vision–based assisted tele–operation of a dual–arm hydraulically actuated robot for pipe cutting and grasping in nuclear environments," *Robotics*, vol. 8, no. 6: 42, pp. 1–24, 2019.

[5] O. Albrecht, M. Bandala, S. D. Monk, and C. J. Taylor, "Control of hydraulically–actuated manipulators with dead–band and time–delay uncertainties," in *3rd UK–RAS Conference for PhD Students and Early–Career Researchers*, Remote Conference, 2020.

[6] I. Tsitsimpelis, C. J. Taylor, B. Lennox, and M. J. Joyce, "A review of ground–based robotic systems for the characterization of nuclear environments," *Progress in Nuclear Energy*, vol. 111, pp. 109–124, 2019.

[7] N. Marturi, A. Rastegarpanah, C. Takahashi, M. Adjigble, R. Stolkin, S. Zurek, M. Kopicki, M. Talha, J. A. Kuo, and Y. Bekiroglu, "Towards advanced robotic manipulation for nuclear decommissioning: A pilot study on tele-operation and autonomy," in *IEEE Robotics & Automation for Humanitarian App.*, Kollam, 2016.

[8] H. Deng, J. Luo, X. Duan, and G. Zhong, "Adaptive inverse control for gripper rotating system in heavy-duty manipulators with unknown deadzones," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 7952–7961, 2017.

[9] B. Magyar, C. Hős, and G. Stépán, "Influence of control valve delay and dead zone on the stability of a simple hydraulic positioning system," *Mathematical Problems in Engineering*, vol. 2010, p. 15, 2010.

[10] P. C. Young, *Recursive Estimation and Time Series Analysis: An Introduction for the Student and Practitioner*. Springer, 2011.

[11] C. J. Taylor, P. C. Young, W. Tych, and E. D. Wilson, “New developments in the CAPTAIN Toolbox for Matlab with case study examples,” in *18th IFAC Symposium on System Identification (SYSID)*, Stockholm, Sweden, July 2018.

[12] Y.-J. Pan, H. J. Marquez, and T. Chen, “Stabilization of remote control systems with unknown time varying delays by LMI techniques,” *International Journal of Control*, vol. 79, no. 7, pp. 752–763, 2006.

[13] Y. Wang, L. Gu, B. Chen, and H. Wu, “A new discrete time delay control of hydraulic manipulators,” *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 231, no. 3, pp. 168–177, 2017.

[14] Y. Lin, “Controller Design for Hydraulic Position Control Systems,” Ph.D. dissertation, University of Saskatchewan, 2011.

[15] M. M. Olsen, J. Swevers, and W. Verdonck, “ML identification of a dynamic robot model: Implementation issues,” *Int. J. Robotics Research*, vol. 21, pp. 9–96, 2001.

[16] M. Gautier and P. Poignet, “Extended Kalman filtering and weighted LS dynamic identification of robot,” *Control Engineering Practice*, vol. 9, pp. 1361–1372, 2001.

[17] M. Gautier, A. Janot, and P. O. Vandanjon, “A new closed–loop output error method for parameter identification of robot dynamics,” *IEEE Transactions on Control SystemTechnology*, vol. 21, pp. 428–444, 2013.

[18] E. Wernholt and S. Gunnarsson, “Estimation of nonlinear effects in frequency domain identification of industrial robots,” *IEEE Transactions on Instrumentation and Measurement*, vol. 57, pp. 856–863., 2008.

[19] A. Janot, P. O. Vandanjon, and M. Gautier, “An instrumental variable approach for rigid industrial robots identification.” *Control Eng. Practice*, vol. 25, pp. 85–101, 2014.

[20] C. J. Taylor, E. M. Shaban, M. A. Stables, and S. Ako, “Proportional–integral–plus control applications of state–dependent parameter models,” *IMECHE Proceedings Part I: Journal of Systems and Control Engineering*, vol. 221, no. 17, pp. 1019–1032, 2007.

[21] A. Janot, P. C. Young, and M. Gautier, “Identification and control of electro–mechanical systems using state–dependent parameter estimation,” *International Journal of Control*, vol. 90, pp. 643–660, 2017.

[22] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, “Design of HyQ -A hydraulically and electrically actuated quadruped robot,” *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, vol. 225, no. 6, pp. 831–849, 2011.

[23] S. Schaal, “The SL simulation and real-time control software package,” University of Southern California, Tech. Rep., 2007.

[24] M. R. Sirouspour and S. E. Salcudean, “Nonlinear control of hydraulic robots,” *IEEE Transactions on Robotics and Automation*, vol. 17, pp. 173–182, 2001.

[25] A. Kotzev, D. B. Cherchas, P. D. Lawrence, and N. Sepehri, “Generalized predictive control of a robotic manipulator with hydraulic actuators,” *Robotica*, vol. 10, pp. 447–459, 1992.

[26] S. K. Dwivedy and P. Eberhard, “Dynamic analysis of flexible manipulators, a literature review,” *Mechanism and Machine Theory*, vol. 41, pp. 749–777, 2006.

[27] T. C. S. Hsia, T. A. Lasky, and Z. Guo, “Robust independent joint controller design for industrial robot manipulators,” *IEEE Transactions on Industrial Electronics*, vol. 38, no. 1, pp. 21–25, 1991.

[28] P. H. Chang and J. W. Lee, “A model reference observer for time-delay control and its application to robot trajectory control,” *IEEE Transactions on Control Systems Technology*, vol. 4, no. 1, pp. 2–10, 1996.

[29] H.-S. Jeong and C.-W. Lee, “Time delay control with state feedback for azimuth motion of the frictionless positioning device,” *IEEE/ASME Transactions on Mechatronics*, vol. 2, no. 3, pp. 161–168, 1997.

[30] P. H. Chang and S. J. Lee, “A straight-line motion tracking control of hydraulic excavator system,” *Mechatronics*, pp. 119–138, 2002.

[31] J. Lee, C. Yoo, Y. S. Park, B. Park, S.-J. Lee, D. G. Gweon, and P. H. Chang, “An experimental study on time delay control of actuation system of tilt rotor unmanned aerial vehicle,” *Mechatronics*, vol. 22, no. 2, pp. 184–194, 2012.

[32] J. Lee, H. Dallali, N. Tsagarakis, and D. Caldwell, “Robust and model-free link position tracking control for humanoid COMAN with multiple compliant joints,” *IEEE-RAS International Conference on Humanoid Robots*, vol. 2015-Febru, no. February, pp. 1–7, 2015.

[33] B. U. Rehman, M. Focchi, J. Lee, H. Dallali, D. G. Caldwell, and C. Semini, “Towards a multi-legged mobile manipulator,” in *Proceedings IEEE International Conference on Robotics and Automation*. Institute of Electrical and Electronics Engineers Inc., June 2016, pp. 3618–3624.

[34] J. Lee, P. H. Chang, K.-H. Seo, and M. Jin, “Stable gain adaptation for time-delay control of robot manipulators,” in *IFAC-PapersOnLine*, vol. 52, no. 15, 2019, pp. 217–222.

[35] G. Licskó, A. Champneys, and C. Hős, “Dynamical analysis of a hydraulic pressure relief valve,” *Proceedings of the World Congress on Engineering*, vol. II, no. 1, 2009.

[36] S. Ben Atia, A. Messaoud, and R. Ben Abdennour, “An online identification algorithm of unknown time-varying delay and internal multimodel control for discrete non-linear systems,” *Mathematical and Computer Modelling of Dynamical Systems*, vol. 24, no. 1, pp. 26–43, 2017.

[37] Touzri M, Naceur M, and Soudani D, “New internal multi-model controller for a linear process with a variable time delay,” *International Journal of Control, Energy and Electrical Engineering (CEEE)*, vol. 1, pp. 1–9, 2014. [Online]. Available: https://www.researchgate.net/publication/273257040

[38] Y. Zhao, A. Fatehi, and B. Huang, “A data-driven hybrid ARX and markov chain modeling approach to process identification with time-varying time delays,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 4226–4236, 2017.

[39] Y. Ma, S. Kwak, L. Fan, and B. Huang, “A variational Bayesian approach to modelling with random time-varying time delays,” in *Proceedings of the American Control Conference*, 2018, pp. 5914–5919.

[40] X. M. Ren and A. B. Rad, “Identification of nonlinear systems with unknown time delay based on time-delay neural networks,” *IEEE Transactions on Neural Networks*, vol. 18, no. 5, pp. 1536–1541, 2007.

[41] J. Q. Huang and F. L. Lewis, “Neural-network predictive control for nonlinear dynamic systems with time-delay,” *IEEE Transactions on Neural Networks*, vol. 14, no. 2, pp. 377–389, 2003.

[42] W. Michiels, V. Van Assche, and S. I. Niculescu, “Time-delay systems with a controlled time-varying delay: Stability analysis and applications,” in *Proceedings of the IEEE Conference on Decision and Control*, vol. 5, 2004, pp. 4521–4526.

[43] Y.-P. Huang, “Robust control of uncertain time-delay systems,” Ph.D. dissertation, Louisiana State University and Agricultural & Mechanical College, 2001.

[44] K. F. Chen and I. K. Fong, “Stability analysis and output-feedback stabilisation of discrete-time systems with an interval time-varying state delay,” *IET Control Theory and Applications*, vol. 4, no. 4, pp. 563–572, 2010.

[45] J. G. Dawson and Z. Gao, “Fuzzy logic control of linear systems with variable time delay,” in *IEEE International Symposium on Intelligent Control*, 1994, pp. 5–10.

[46] M. Sbarciog, R. De Keyser, S. Cristea, and C. De Prada, “Nonlinear predictive control of processes with variable time delay. A temperature control case study,” in *Proceedings of the IEEE International Conference on Control Applications*, 2008, pp. 1001–1006.

[47] C. J. Taylor, P. C. Young, and A. Chotai, *True Digital Control: Statistical Modelling and Non–Minimal State Space Design*. John Wiley and Sons, 2013.

[48] C. J. Taylor, A. Chotai, and P. C. Young, “Proportional–Integral–Plus (PIP) control of time delay systems,” *IMECHE Proceedings Part I: Journal of Systems and Control Engineering*, vol. 212, no. 1, pp. 37–48, 1998.

[49] J. P. Barbot, G. Zheng, T. Floquet, D. Boutat, and J. P. Richard, “Delay estimation algorithm for nonlinear time-delay systems with unknown inputs,” in *IFAC Proceedings Volumes*, vol. 45, no. 14, 2012, pp. 237–241.

[50] F. Chen, H. Garnier, and M. Gilson, “Robust identification of continuous-time models with arbitrary time-delay from irregularly sampled data,” *Journal of Process Control*, vol. 25, pp. 19–27, 2015.

[51] A. Padilla, H. Garnier, P. Young, F. Chen, and J. Yuz, “Identification of continuous-time models with slowing time-varying parameters,” *Control Engineering Practice*, vol. 93, 2019.

[52] Y. Tan, “Time-varying time-delay estimation for nonlinear systems using neural networks,” *Int. J. Appl. Math. Comput. Sci*, vol. 14, no. 1, pp. 63–68, 2004.

[53] V. Vandoren, “Control Engineering: Fundamentals of cascade control,” aug 2014. [Online]. Available: https://www.controleng.com/articles/fundamentals-of-cascade-control/