Control of hydraulically–actuated manipulators with dead–band and time–delay uncertainties*

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***Abstract*—The research behind this article is motivated by robotic operations in radiologically contaminated environments, notably for nuclear decommissioning. However, the experiments reported within are based on a recently reconfigured, hydraulically–actuated, dual manipulator robot that is being used for R&D into both tele–operation and autonomy in a non–active laboratory setting. One element of this research concerns the development of novel control systems to address time–delay and deadband uncertainties. The article briefly discusses some preliminary results and plans in this regard. Recent improvements to the hardware demonstrator are also described.**

***Index Terms*—nuclear decommissioning, hydraulic actuators, deadband, time–delay, uncertainty**

I. Introduction

A significant number of nuclear facilities around the world have reached the end of their useful life and hence are in the process of decommissioning. Since it is environmentally unfriendly and dangerous for plant workers, many decommissioning tasks are accomplished with robots, for which direct tele-operation is standard [1]. 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 more efficient and robust embedded electronics and sensors, there is significant interest in semi-autonomous capabilities [2]–[4].

The present article concerns a previously developed dual-manipulator robotic platform [5]. The system has recently been reconfigured, hence the new hardware framework and control software are described (section II). The broad aim is to develop semi-automatic control systems that reduce operator workload, speeding up task execution and reducing operator training time, whilst minimizing the introduction of additional sensors and other components. Due to limited sensor data availability in nuclear environments, a system for grasping generic objects could be unreliable. As a result, the developed approach is based on the concept of multiple subsystems for common tasks under one user interface: one for pipe cutting, one for pick and place operations, and so on. This aims to reduce the complexity of the problem, potentially leading to improved performance and reliability. Furthermore, cognitive workload is reduced by tailoring the information shown to the operator. The research focuses on pipe cutting as an illustration of the generic approach, since this is a common repetitive task [6].

Motivated by preliminary testing that highlights limitations in the performance, one aspect of the research programme concerns the development of improved 'low-level' control systems for hydraulic manipulators, such that they can more effectively achieve the 'higher-level' task orientated objectives. In this regard, it is notable that uncertainties and nonlinearities, including actuator deadbands and time-delays, are not always fully addressed in the literature [7]. In fact, the two major challenges in high performance positioning and tracking stabilisation of robot manipulators, are the friction between moving parts and the deadband of the actuators.

The present work utilises a state-dependent parameter (SDP) framework to characterise the manipulators. The parameters of SDP models are functionally dependent on measured variables, such as joint angles and velocities, normally defined in discrete-time terms [5]. However, in contrast to other recent research into SDP systems for the same machine [6], the present work utilises a new *continuous-time* SDP model that is not dependent on the sampling interval, and uses this to investigate uncertainties (including time-variations) in the system time-delay and deadband (section III).

II. Reconfigured Hardware

The laboratory demonstrator used in this article consists of two HYDROLEK HLK-7W manipulators, each a 6-degrees-of-freedom articulated arm, with a seventh actuator for the gripper. Whilst the original set-up is described by reference [6], a ball valve, pressure gauge and new pressure pump were added in 2019. Fig. 1 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

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(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 was recently 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 [6] for a recent reference.

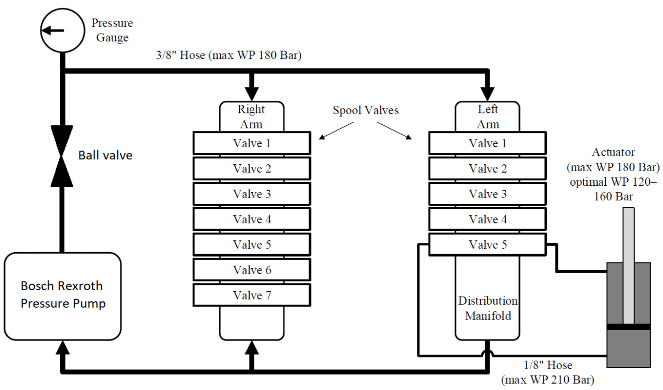

Fig. 1. Schematic diagram of the reconfigured hydraulic system.

III. Methodology and Preliminary Results

The new continuous time SDP model for hydraulic manipulators is identified in three stages, as follows:

Step 1. Open-loop step experiments, such as those shown in Fig. 2, suggest that a first order linear differential equation,

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

provides an approximate representation of individual joints, with a_1, b_1 and the time-delay τ estimated using the SRIVC algorithm in the CAPTAIN toolbox [8]. 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.

Step 2. Further analysis of experimental data using SDP methods, suggests that $a_1 \approx 0$ is time invariant, whilst b_1 is a state dependent parameter. 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. For brevity, further details are omitted from this article, but see [6] for an example of this static nonlinearity, albeit expressed in discrete–time terms. However, these equations and the prior work cited above, all assume time–invariant τ, whereas Fig. 2 illustrates how the actual recorded time-delays can vary from experiment to experiment (in the case of Fig. 2) or during normal operation (more generally), hence introducing a substantial challenge for control design.

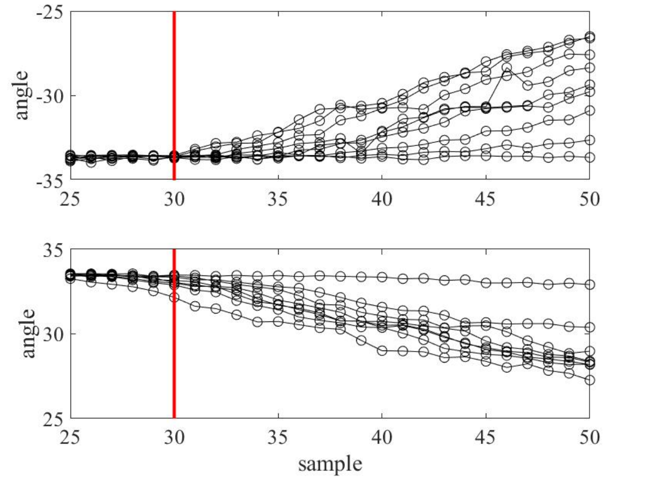

Fig. 2. Open–loop experiments for an illustrative manipulator joint using step inputs for a range of magnitudes, with the initially estimated time-delay shown as a solid vertical line (i.e. sample 30). These graphs show the actual recorded time-delays range from 18 samples to 29 samples because of variations in the deadband. The upper and lower subplots show the manipulator being raised and lowered respectively, each trace representing a different experiment.

IV. Conclusions

This article has described the updated configuration of a robotic platform used for R&D. The SDP approach to system identification for hydraulic manipulators is briefly reviewed, here with the equations adapted into a new continuous-time form. This new formulation is designed to facilitate research into models and control systems that address time-delay and related deadband nonlinearities. In the latter regard, the authors are developing and presently evaluating both conventional and nonsingular terminal sliding mode control systems, in addition to various forms of SDP based control.

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