Controlling a quadruple tanks rig with PLCs as a Masters dissertation project

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Controlling a quadruple tanks rig with PLCs as a Masters dissertation project

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Abstract: We report on a successful themed Masters level project. Ten students addressed a single multivariable control problem using a variety of control algorithms and hardware platforms. The use of an OPC server provides different control structures that can be used to design controllers with different specifications such as bandwith and noise rejection.

Keywords: Teaching aids for control engineering, programmable logic controllers, decoupling precompensator, lead-lag compensation, H_∞-control, fuzzy logic control, optimal control, sliding mode control, PID control, model predictive control, internal model control.

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1. INTRODUCTION

1.1 Background

The University of Manchester has a long and proud tradition of teaching control to both undergraduate and masters students (Atherton, 2008; Smith, 1996). At present our MSc course in Advanced Control and Systems Engineering attracts circa 60 students per year. A third of the course's credits are earned on a dissertation project; furthermore a Distinction in the project is necessary in order to gain a Distinction over all. Present numbers place considerable strain on project allocation. In the academic year 2011-2012 we trialled so-called "themed projects" where students are assigned similar but separate projects; some of the supervision time is replaced by group meetings and group study. In this paper we report on one such themed-project where students were asked to control a four tanks apparatus and, as an option, to use PLCs to implement their controller. Ten students were allocated to the project leading to the dissertations of Asabor (2012); Date (2012); Goewam (2012); Gopalkrishnan (2012); Kumar (2012); Li (2012); Okolo (2012); Pachemanov (2012); Subramanian (2012); Zhang (2012)[1].

1.2 Students' skills

Most students on our course come straight from undergraduate studies. Nevertheless a signifcant minority have worked in industry and have some experience of industrial control implementation.

In the first semester of the MSc they become well-versed in classical control, state-space and system identifation techniques. They also take a specialist course in process control relevant to this project. In the second semester they are introduced to more advanced linear and nonlinear control techniques. For this academic year we introduced a new course "Applied Control" in which students gained hands-on experience of real-time implementation issues; this course is supported directly by National Instruments.

1.3 Experimental apparatus

The project is focused on the quadruple tanks apparatus. This was introduced by Johansson (2000) as a teaching laboratory suitable for teaching multivariable control. Four tanks are arranged as in Figs 1 and 2. In particular the rig may be configured to have a nonminimum phase zero making the control challenging. In his original design the zero can be adjusted continuously with a valve setting. For this rig we used the Quanser four tanks apparatus configured by combining a pair of coupled tank rigs. This has a discrete number of settings determined by width of pipe and apperture size; some of these settings entail nonminimum phase dynamics. Although perhaps lacking the elegance of the original design, this set up is very useful for a shared resource; students can reconfigure the apparatus to their "own" setting regardless of usage history.

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[1] Copies of any or all of these are available from the first author by request

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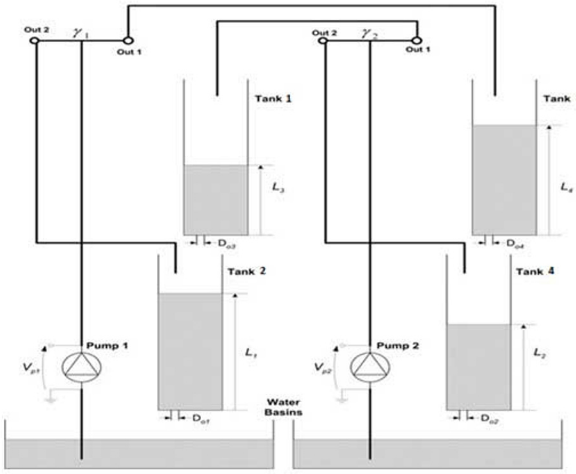

Fig. 1. Schematic of the quadruple tank rig (adapted from the Quanser manual).

Fig. 2. The Quanser rig set up in our laboratory (Subramanian, 2012).

A further advantage of the Quanser rig is that it comes with hardware (e.g. the Quanser Real-time Control Board) and software (e.g. QuARC) that allows real-time interface between Matlab and the sensors and actuators of the rig. It is then straightforward for students to test control designs in Matlab/Simulink and then implement them directly onto the actual device. All ten students transfered their control designs to practical implementation.

We have a number of PLCs, including Siemens, DirectLOGIC and Rockwell. For this project we opted to offer Siemens S-7 300 (Fig 3) and DirectLOGIC DL06 (Fig 5 PLCs. Several modules of each were available. The stated aim was to implement advanced control on a PLC, although students were welcome to focus on control design without PLC implementation. A fall back option was to use the PLC as a communication link between the rig and a PC via an OPC server, where the control would run; the availability of the Matlab/Simulink OPC toolbox means this is a relatively straightforward option while sufficiently interesting to stimulate the students, and changing significantly the bandwidth constraints of the system. We were not prescriptive for the students' choices, save to encourage them each to choose different options.

The Siemens S-7 300 is a modular central processing unit (CPU) type programmable logic controller(PLC) developed and manufactured by Siemens. Students could use one of its versions, namely the SIMATIC S7-300 CPU 314-2 PN/DP. Salient features for this project were (SIMATIC S7-300 Manual, Siemens ST 70, Section 4, 2003 and Date, 2012):

- It is a high processing performance CPU especially in floating point and binary arithmetic.
- Onboard Message Passing Interface (MPI).
- It has comprehensive integrated system diagnosis.
- Supports the insert of Simatic Engineering tools.

The DirectLOGIC DL06 (D0-06DD1) is a micro PLC from the DL06 Micro PLC family that has 20 in-built inputs and 16 in-built outputs. It supports 4 option cards such as the analogue I/O module, high-speed counters module, and others. The DL06 PLC has a total of 14.8K words of memory. This memory capacity is split into two, that is, 7.6K words for ladder memory and 7.6K words of V-memory. The DL06 also includes a RAM with the CPU which stores system parameters, V-memory, and other variables not available in the application program.

Fig. 3. Siemens S7-314-2 PN/DP PLC CPU (Siemens AG Brochure, 2011).

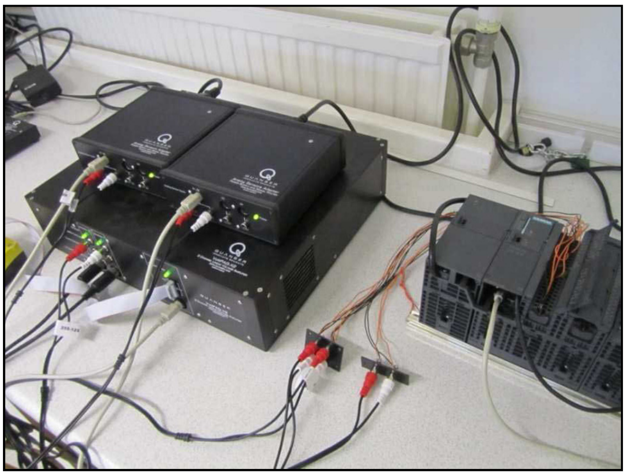

Fig. 4. Wiring between the Siemens PLC and the Quanser board (from Date, 2012).

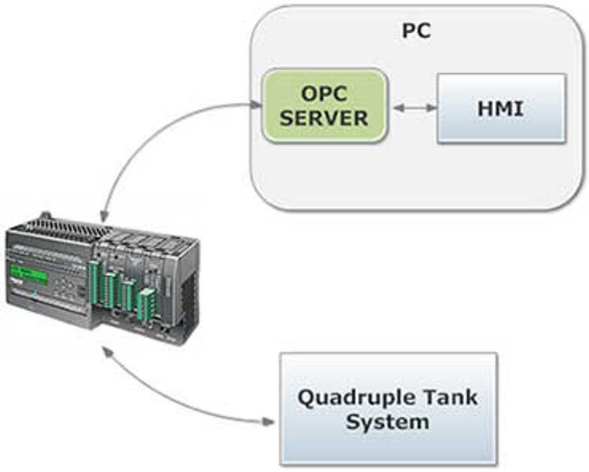

Fig. 5. The DirectLOGIC DL06 configured to act as a communications link between the PC and the Quanser hardware (Asabor, 2012).

It has two in-built serial ports (DirectSOFT manuals and Asabor, 2012).

1.4 Supervision

There were two lead academic supervisors of the project - the first two authors of this paper. In addition there were four demonstrators - the latter four authors. Students and demonstrators met a as a team once a week with at least one of the lead academics present (usually both). Meanwhile students met with either a lead academic or a demonstrator individually at least once a week for a one-one session.

2. SCOPE OF PROJECTS

An overview of projects is shown in Table 1. We can make the following observations. A wide range of control techniques were attemped, from simple PI to $\mathcal{H}_\infty$ and sliding mode techniques. However only two students implented their controller in nonminimum phase configuration on the rig (several considered it in simulation and posed the online implementation as “further work”). Perhaps coincidentally one of these was the only student not to test his design in simulation first. Half the students implemented their controllers on both Quanser and their chosen PLC. Only one student chose not to implement his controller on a PLC. The split between the choice of Siemens or DirectLOGIC PLC was fairly even, as was the split between using the PLC for communications only or as the control platform. However most students using the Siemens PLC opted to use the PLC as the control platform, while most students using the DirectLOGIC PLC used it for communication.

We discuss the project scope in more detail below. Two important aspects of the projects not highlighted in Table 1 are system identification and use of SCADA/OPC server. These are also discussed below.

2.1 Control structures

Table 1 shows the range of control structures successfully implemented on the hardware rig. Some of these structures are taught explicitly as part of the taught component of the MSc course. Others are, at best, mentioned in passing. Students reported several other control structures in their dissertations; typically different controllers (or control tuning) were compared in simulation and one of these chosen for final implementation.

One disappointment was that only two students (Kumar, 2012; Pachemanov, 2012) addressed the nonminimum phase zero on the rig itself. We speculate that this is most likely a reflection of the severe time constraints under which the project was run. It is notable that one of these students skipped the simulation stage and experimented with his controller (model predictive control run in Matlab) directly on the plant; the other was the first to successfully configure communication between a PLC and the rig. An additional factor may be that at present there is little multivariable control taught on the course (the course covers several state space control designs including model predictive control and $\mathcal{H}_\infty$ control, but the specific structures of multivariable control systems are not emphasised); students may not have been immediately comfortable with the concept of a right half plane zero that cannot be seen directly in the transfer function numerator polynomials.

2.2 System identification

The plant is straightforward to model - the dynamics of each tank from *flow in* to *level height* may be well-approximated as a first order process. Hence the transfer function matrix can be expressed using first and second order transfer function elements. Additional dynamcis (for example motor response and sensor characteristics) are fast in comparison and can be ignored. A better approximation can be found if the parameters of the first order elements are considered height dependent - this was addressed in the gain-scheduling approach of Subramanian (2012).

Students on the course cover system identification in two separate modules. They were keen to test their new-found skills and most carried out tests using PRBS excitation signals. Although the option was given, none chose to make

$$G(s) = \begin{bmatrix} \dfrac{1.8109}{65.033s+1} & \dfrac{1.5}{(65.033s+1)(26.462s+1)} \\ \dfrac{2.6823}{(114.72s+1)(38.0296s+1)} & \dfrac{3.4565}{114.72s+1} \end{bmatrix} \tag{1}$$

system identificaiton the *focus* of their project; rather they viewed it as a necessary (and interesting) preliminary to control design and implementation. Typical experimental data for one channel is shown in Fig 6 with corresponding validation data shown in Fig 7 (Date, 2012). A typical model for the two-input two-output plant (Date, 2012) is given in equation (1).

In addition, several students worked together to obtain models. In many cases they peformed the experiment together but analyse the data separately - this mode of work is typical for more formal laboratory work when part of taught courses. One difficulty was that this made it hard to accredit the specific contributions of this aspect of the work.

2.3 Results

Control of the plant using Quanser hardware and software is relatively straightforward. As students had implemented practical controllers in previous courses they were prepared to deal with signal offsets etc. Fig 8 shows a typical set of results, in this case from Zhang (2012) using sliding mode control and demonstrating decoupling.

The intention of allowing the option of using PLCs as a communication tool was that students could focus on real-time implementation aspects without worrying further about control design. It turned out that this option entailed two additional design considerations:

(1) The sample rate was typically slower than using direct connections. Control design had to take this into account - in particular with respect to performance at high frequency.
(2) The PLC wiring was less well shielded than the direct connections (see Section 2.4), so that there was more noise in the loop. This affected the choice of closed-loop bandwidth.

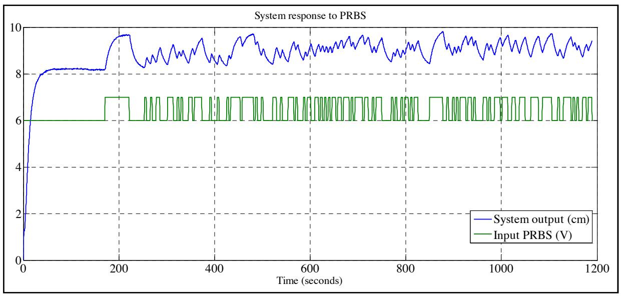

Fig. 6. Typical experimental data for system identification Date (2012).

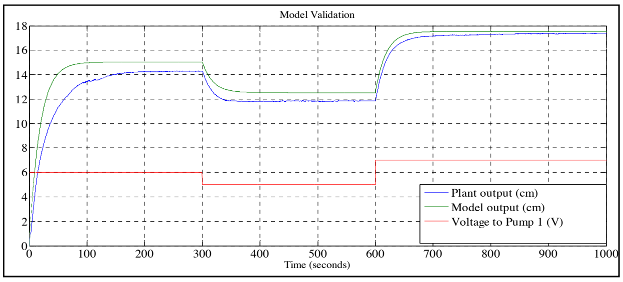

Fig. 7. Typical model validation experiment Date (2012).

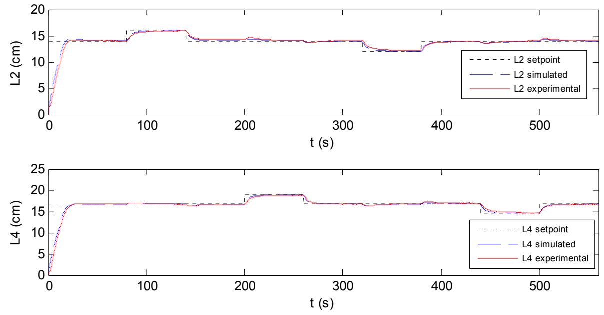

Fig. 8. Results using Quanser hardware and software Zhang (2012).

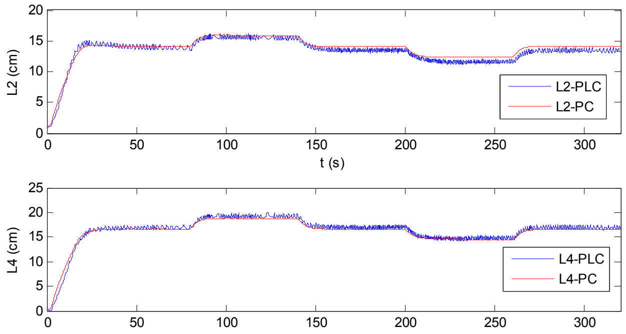

Fig. 9. Results using PLC implementation compared with results using Quanser hardware and software Zhang (2012).

Of course, similar issues arose when controllers were implemented directly on the PLCs. Fig 9 compares typical performance using PC and PLC control. Once again, this is from Zhang (2012).

Of the designs using PLCs as a communication channel, the most interesting was probably that of Kumar (2012). Here the Matlab MPC toolbox was used to control the plant when configured to have a nonminimum phase zero. In other designs classical PI and lead-lag controllers, internal model control and sliding mode control were all implemented directly on PLCs (see Table 1).

2.4 SCADA and OPC server

Several students built their own SCADA interfaces, using tools such as the IGSS SCADA system developed by 7-Technologies A/S. This SCADA has a free version limited to 50 objects (IGSS FREE50 [2]), sufficient and suitable for

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[2] This version can be downloaded on http://igss.schneider-electric.com/products/igss/download/free-scada.aspx

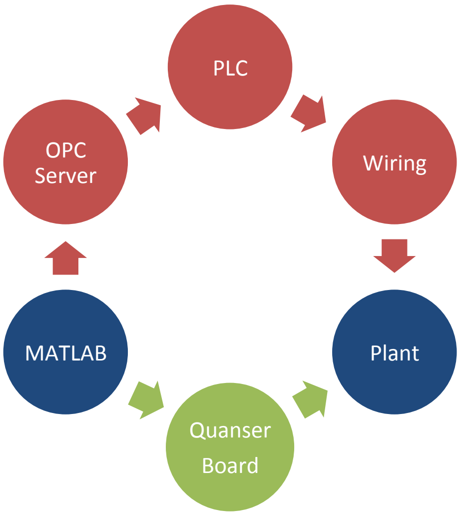

Fig. 10. Different communications between Simulink and the tanks. In both cases the controller is running in Simulink. In the red path, the OPC server provides a comunication between MATLAB and the PCL via the OPC toolbox; the signals reach the plant with additional wiring. In the green path, the communication is based on the Quanser configuration, where the signals reach the plant via the Quaser board.

all students' projects. Four such examples are shown in Figs 12a, 12b, 12c and 12d. All were built using the IGSS FREE50.

The communication between the SCADA and the PLC required an OPC server (see Fig. 5). The OPC server used by the students was the demo version of KEPServerEX v5[3]; this demo restricts the experiments to two hours, which was enough for the projects. If the original motivation of using the OPC server was to support the communication between the SCADA and the PLC, it became a versatile tool. It provides students a straightforward implementation of their controllers via PLC (see Fig. 10) with minimal code on the PLC itself. It makes an interesting exercise in control design for the student since sampling time and noise levels are significantly different in comparison with the Quanser hardware. Since students began the project more familiar with Simulink than with PLC programming, they were comfortable using this to test controller designs before coding the PLC.

A further configuration that can be used with the OPC server is the proposed in Fig. 11. Both configurations run the controller in the PLC, but with significantly different levels of noise. This configuration was not used by our students but will be proposed for future projects.

3. DISCUSSION

The projects were popular, and the students did well. Of a cohort of 49 students, 14 put it as first choice and 6 as second choice. Projects were allocated independently of examination results, yet four students received a Distinction level grade for their dissertation (of whom two received Distinction overall). In fact students' average grade for the

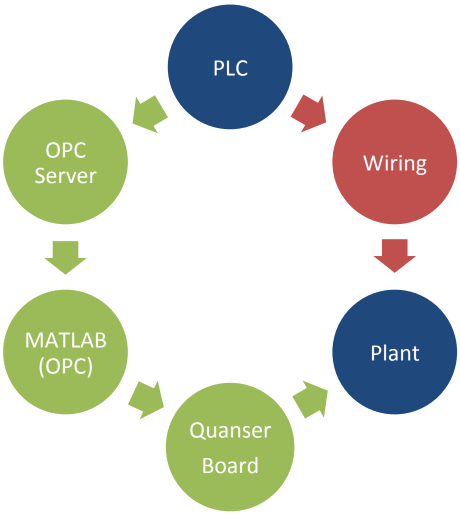

Fig. 11. Different communications between PLC and the tanks. In both cases the controller is running on the PLC. In the red path, the PLC signals reach the plant with additional wiring. In the green path, the SCADA system is used for the communication between the PLC and MATLAB; then the signals reach the plant via Quaser board.

disseration was 3.3 marks (out of 100) higher than for their examination results; the average for the whole cohort is a rise of 1.3 marks.

One potential problem was allocation of credit where students shared work. We only gave credit for work that was clearly independent, and asked students to acknowledge where results had been obtained as part of a team. In this case several students shared data from system identification experiments but then analysed the data independently. Similarly, where students share ideas such as the use of a particular OPC server, then it is hard to identify and credit the innovator.

An advantage of the themed project format was that students were encouraged to, and did, form a one-one rapport with a postgraduate student in addition to their time with academic staff. One student has elected to stay and study for a PhD. It was clear that many of the students enjoyed the team atmosphere of the projects. Nevertheless, it remains open to question whether some students would have done better with more one-one interaction with academic staff.

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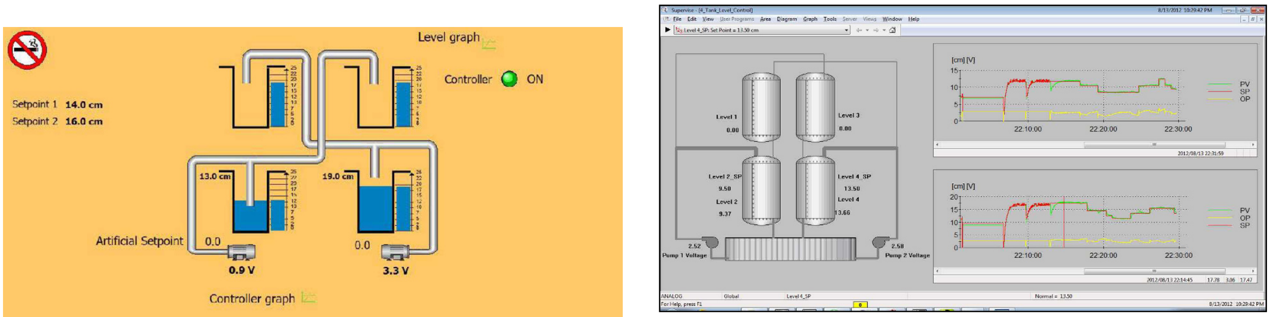
[3] A demo version can be downloaded on http://www.kepware.com/Products/kepserverex_features.asp

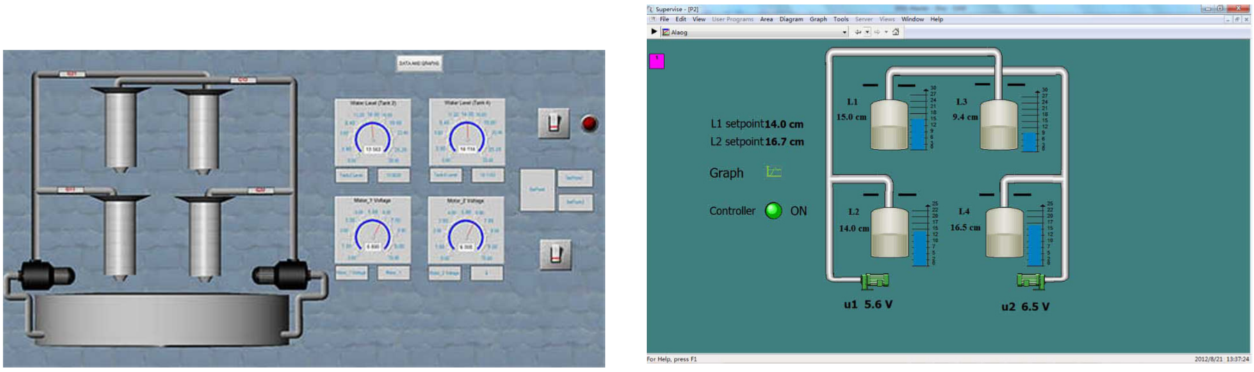
Student	Control structure	Simulation	Quanser	Siemens (comms)	Siemens (control)	DL (comms)	DL (control)	NMP
Asabor	Discrete LQG	Y				Y		
Date	Lead-lag with decoupler	Y	Y		Y			
Goewam	$\mathcal{H}_\infty$	Y	Y			Y		
Gopalkrishnan	Fuzzy logic	Y				Y		
Kumar	MPC					Y		Y
Li	LQG	Y	Y					
Okolo	Decentralised IMC	Y	Y				Y	
Pachemanov	IMC	Y			Y			Y
Subramanian	Gain scheduled PI	Y			Y			
Zhang	Sliding mode	Y	Y	Y	Y			

Table 1. Range of projects. All but one student first implemented their control in simulation. Exactly half the students implemented their controller using Quanser hardware interfaced with Matlab on the PC alone. Four students coded their controller on the Siemens PLC. Five students implemented their controller via the DirectLOGIC PLC, but only one of these actually coded the controller on the PLC. Only two students implemented their controller on the actual rig in nonminimum phase mode.



(a) SCADA interface built by Pachemanov (2012)

(b) SCADA interface built by Date (2012)



(c) SCADA interface built by Asabor (2012)

(d) SCADA interface built by Zhang (2012)

Fig. 12. SCADA interfaces

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