Supplementary Document: Evolutionary Design of Controllers for Optimizing Controller Structure and Parameters with Application to Magnetic Levitation System

Bin Xin, *Member, IEEE* , Yipeng Wang, Wenchao Xue,*Member, IEEE*, Tao Cai,
Zhun Fan, *Senior Member, IEEE*, and Jie Chen, *Fellow, IEEE*

I. Supplemental Simulation Results

A. Simulation Diagram

In the application to MLS, 4 components are selected to make up a controller and each solution of this controller optimization problem has 7 controller parameter elements and 24 structure elements. In MATLAB/Simulink, the controller model is built as shown in Fig. 1. As shown this figure, 31 elements (i.e., $k1, k2, \ldots, K31$) need to be optimized to get a controller with satisfactory expected performance indices.

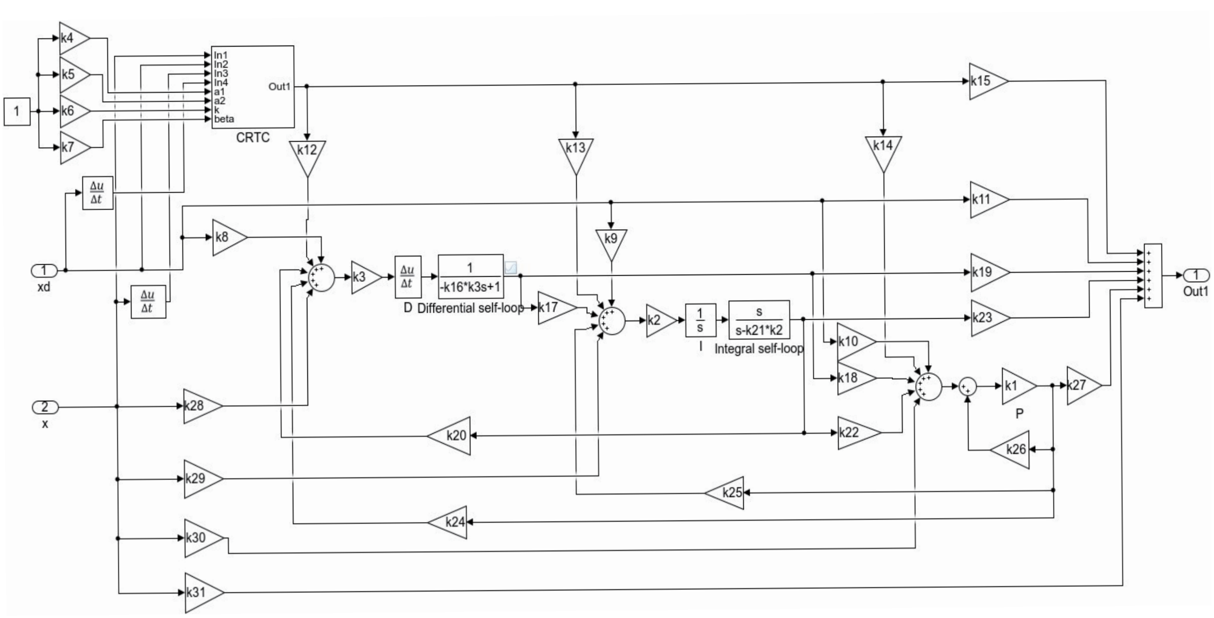
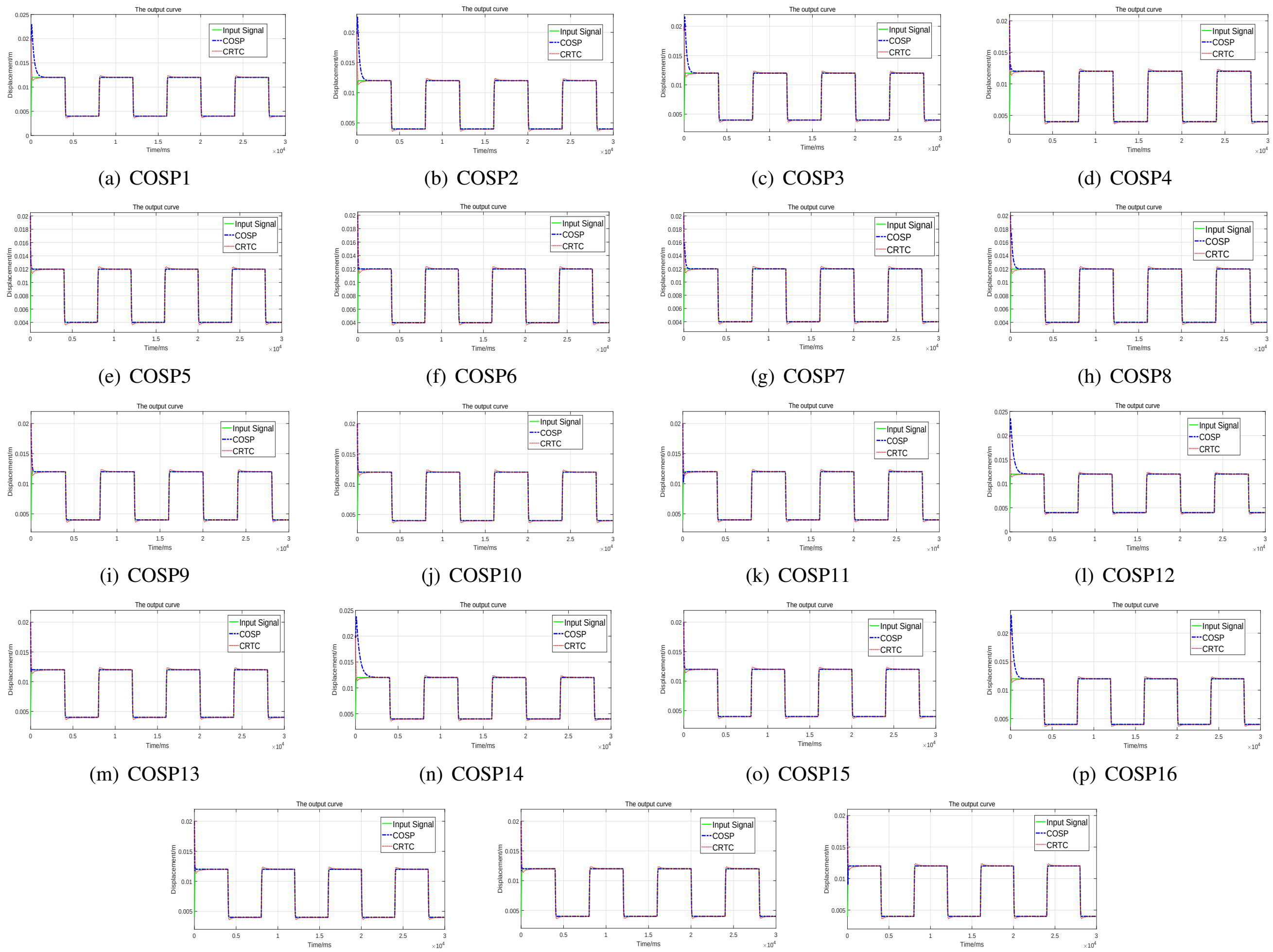


Fig. 1. The model diagram of 4-components controllers for MLS.

B. Statistical Results

Compared with CRTC, the output curves of the obtained COSPs (COSP1∼COSP19) with the $ITAE$ indicator as optimization objective are presented in Fig. 2. As can be seen from Fig. 2, the obtained COSPs have better dynamic tracking characteristics than CRTC except for the first half of the first period. In addition, the output curves of the obtained COSPs with the rise time (tr) as the optimization objective under the constraint of IAE and $overshoot$ are presented in Fig. 3. As shown in Fig. 3, the response speed of the obtained COSPs has been improved which demonstrates the effectiveness of the design of optimization objectives.

Moreover, we also considered the IAE indicator in the design of optimization objective. Taking the IAE indicator as the design goal, the simulation and statistical results are shown in Table I. As shown in Table I, all the IAE, $ITAE$, ts, $overshoot$, $ess2$ indicators of the obtained COSPs are better than CRTC. In summary, about 82.86% of the evaluation indices of the obtained COSPs are superior to those of CRTC while the response speed (namely, the rise time tr) is slightly slower than that of CRTC.



(a) COSP1 (b) COSP2 (c) COSP3 (d) COSP4

(e) COSP5 (f) COSP6 (g) COSP7 (h) COSP8

(i) COSP9 (j) COSP10 (k) COSP11 (l) COSP12

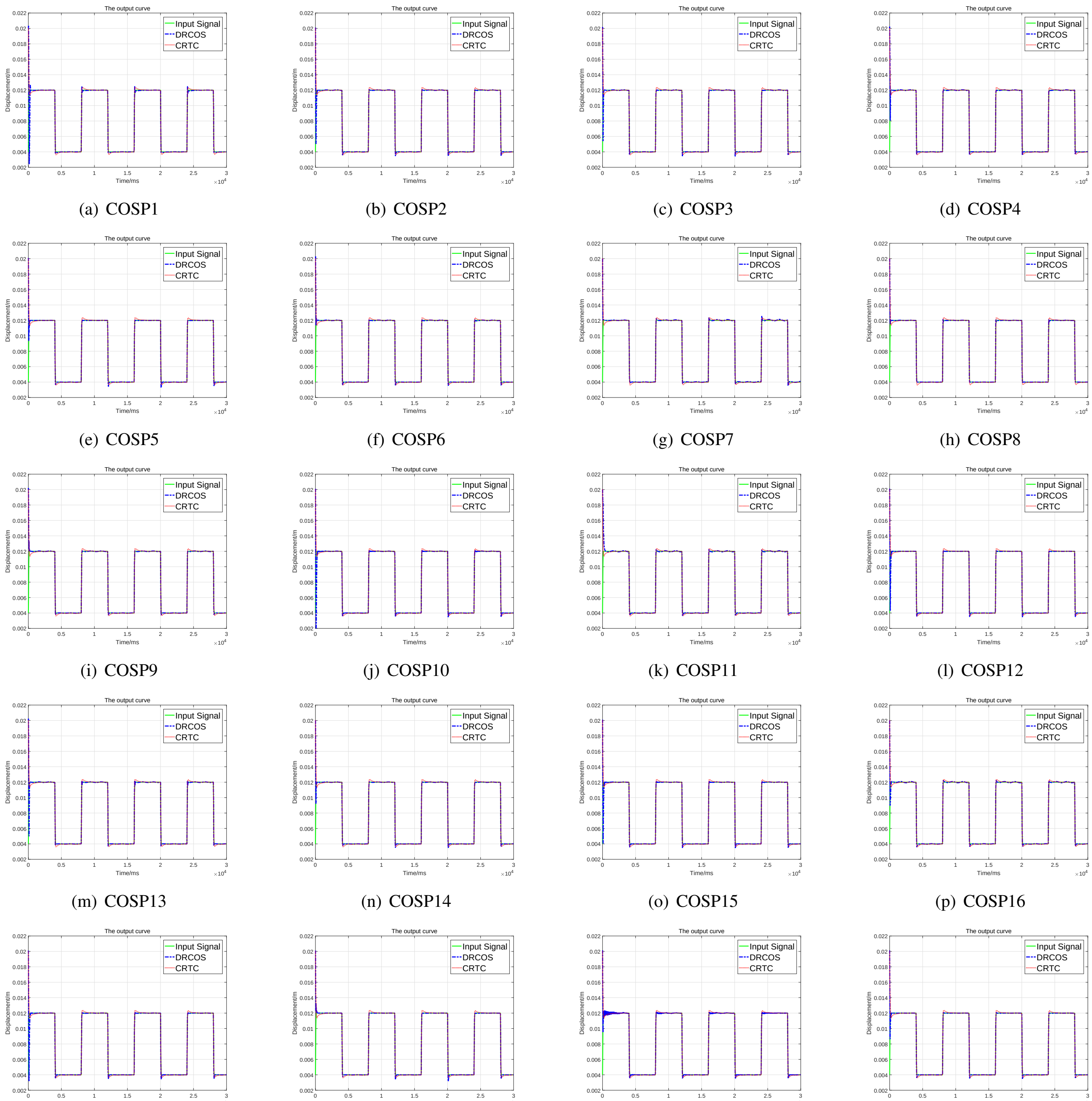
(m) COSP13 (n) COSP14 (o) COSP15 (p) COSP16

(q) COSP17 (r) COSP18 (s) COSP19

Fig. 2. The system output of COSPs with the rise time as the optimization objective compared with CRTC.

TABLE I
STATISTICAL RESULTS OF PERFORMANCE INDICATORS WITH IAE AS THE OPTIMIZATION OBJECTIVE.

controller	tr/s	ts/s	overshoot	ess1	ess2	IAE	ITAE
COSP1	0.08257	0.1175	0.0098	7.6883E-05	5.4590E-07	1.1474E-06	1.7597E-06
COSP2	0.08157	0.1155	0.0029	1.8419E-05	1.1255E-07	2.7928E-06	9.9871E-07
COSP3	0.08157	0.1155	0.0039	1.9369E-05	8.0798E-08	2.7002E-06	7.9020E-07
COSP4	0.08157	0.1160	0.0017	1.6433E-05	7.6735E-08	2.4953E-06	7.1291E-07
COSP5	0.08157	0.1155	0.0062	2.0495E-05	5.7122E-08	2.6819E-06	6.3527E-07
COSP6	0.08157	0.1160	0.0027	1.6798E-05	1.6193E-07	2.8994E-06	1.3532E-06
COSP7	0.08157	0.1158	0.0026	1.8159E-05	1.0780E-07	2.7542E-06	9.6161E-07
COSP8	0.08157	0.1155	0.0209	2.7201E-05	2.4578E-07	3.7683E-06	2.0376E-06
COSP9	0.08200	0.1150	0.0754	4.0884E-05	5.1638E-07	5.5077E-06	4.2050E-06
COSP10	0.08157	0.1160	0.0025	1.8041E-05	1.0786E-07	2.7464E-06	9.6018E-07
COSP11	0.08157	0.1160	0.0020	1.6922E-05	1.1887E-07	2.7025E-06	1.0064E-06
COSP12	0.08257	0.1173	0.0232	1.9565E-04	3.8689E-06	7.1357E-06	9.1917E-06
COSP13	0.08257	0.1172	0.0414	1.8692E-04	6.3587E-06	9.8264E-06	1.3597E-05
COSP14	0.08200	0.1145	0.1242	4.6005E-05	9.1507E-07	7.8680E-06	7.3110E-06
COSP15	0.08257	0.1170	0.0358	1.6028E-04	3.7534E-06	3.8135E-06	5.9631E-06
COSP16	0.08200	0.1143	0.1455	6.4436E-05	1.1702E-06	9.2286E-06	9.3448E-06
COSP17	0.08157	0.1155	0.0035	1.8868E-05	1.3706E-07	2.9205E-06	1.1838E-06
COSP18	0.08157	0.1160	0.0028	1.4264E-05	1.3684E-07	2.4918E-06	1.1763E-06
COSP19	0.08157	0.1160	0.0026	1.8084E-05	1.0929E-07	2.7557E-06	9.7177E-07
COSP20	0.08257	0.1177	0.0421	1.4583E-04	2.0919E-06	1.0324E-05	1.5966E-05
CRTC	0.07643	0.5143	4.1761	8.9204E-05	1.7093E-05	2.4024E-04	2.2498E-04



(a) COSP1 (b) COSP2 (c) COSP3 (d) COSP4

(e) COSP5 (f) COSP6 (g) COSP7 (h) COSP8

(i) COSP9 (j) COSP10 (k) COSP11 (l) COSP12

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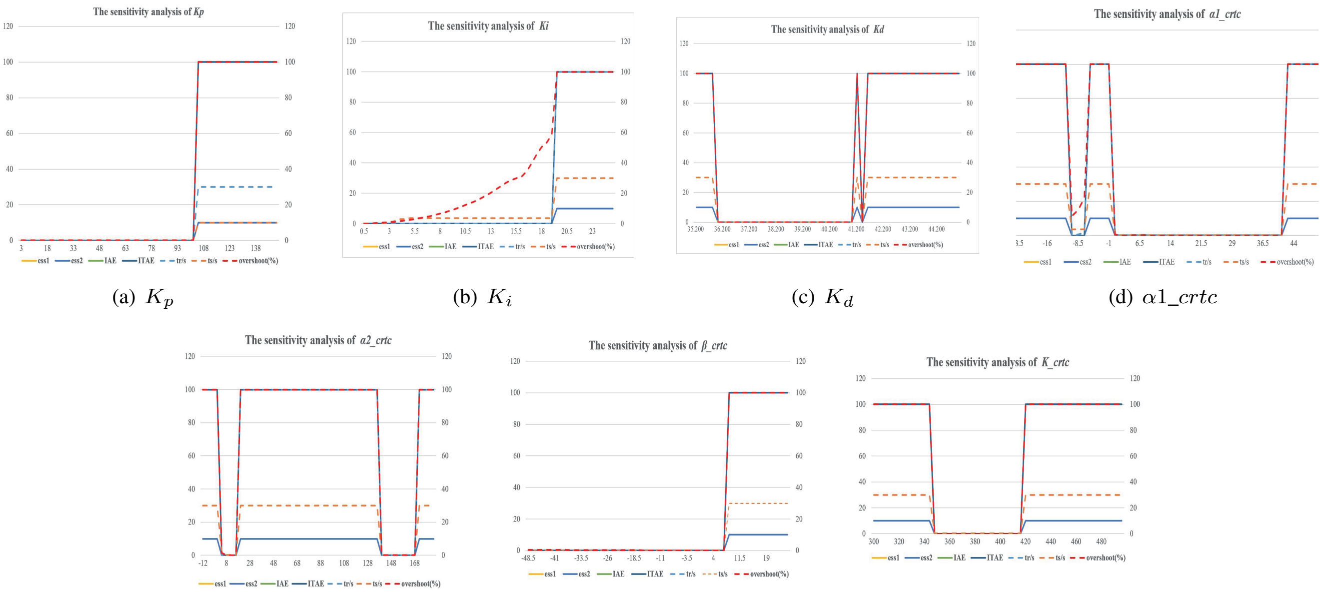
(q) COSP17 (r) COSP18 (s) COSP19 (t) COSP20

Fig. 3. The system output carves of COSPs with the rise time as the optimization objective under the constraint of IAE and overshoot.

C. Parameter Sensitivity Analysis

In order to further analyze the performance of the controllers obtained by the proposed design method, the parameter sensitivity analysis for both plant and controller parameters are conducted. The impacts of the 7 controller parameters optimized in the design process on the controller performance indicators are investigated respectively. Taking the obtained controller COSP1 (see Fig. 3(a)) as an example, the analysis results are shown in Fig. 4. Solid lines correspond to the primary (left) Y-axis and dotted lines correspond to the secondary (right) Y-axis. From this figure, it can be found that the performance of the obtained COSP is still satisfactory if a certain controller parameter varies in a certain range while the other parameters stay the same. Besides, taking the obtained controller COSP1 (see Fig. 3(a)) as an example, the combined impacts of the plant parameters Q and m in MLS on the controller performance indicators are also studied independently and the results are shown in Fig. 5. As this figure shows, as for the considered 7 performance indicators, the control performance of the obtained COSPs will not deteriorate as Q and m change in a certain range. More specifically, the adjustable ranges of K_p, K_i, $\alpha1\_crtc$, and

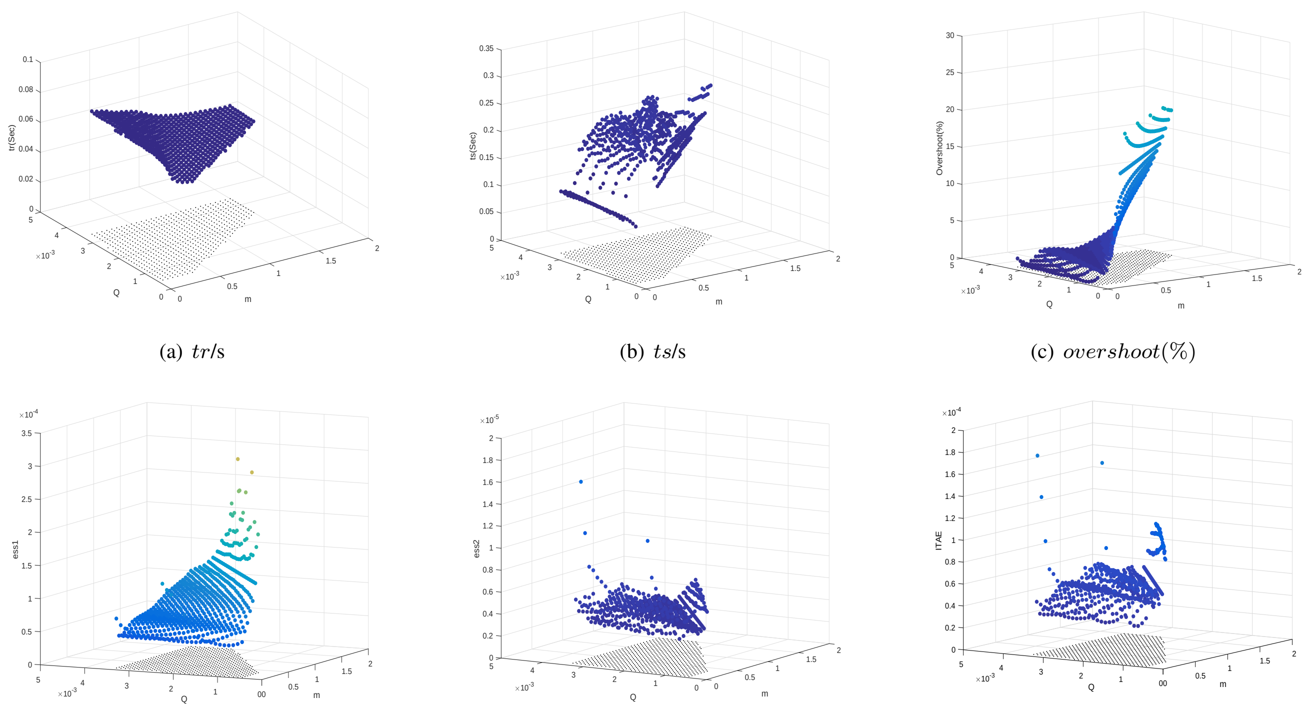
β_crtc are wider than the other 3 parameters, corresponding to the considered performance indices.



(a) K_p (b) K_i (c) K_d (d) $\alpha 1\_crtc$

(e) $\alpha 2\_crtc$ (f) β_crtc (g) K_crtc

Fig. 4. The parameter sensitivity analysis of the controller parameters.



(a) tr/s (b) ts/s (c) $overshoot(\%)$

(d) $ess1$ (e) $ess2$ (f) $ITAE$

Fig. 5. The parameter sensitivity analysis of the plant parameters. This figure shows the change in different performance indicators while the plant parameters vary in the adjustable range (i.e., the black dots in the Q-m plane). When the values of parameters are out of the adjustable range, the control performance will be unstable and corresponding performance indicators are not available.

II. Real-time Experiment on the MLS Testbed

In the real-time experiment, we also carry out the simulation to generate controllers using the proposed design method before the application to the actual system. Consider the practical structure of the MLS testbed, the simulation diagram is built in

MATLAB/Simulink as shown in Fig. 6. Then conduct the proposed design method to generate controllers automatically with the IAE as the optimization objective. An obtained COSP is taken as an example and applied to the actual plant. The selected solution is

$$X = [0.002, 0, 0.0245, 27.7534, 33.6203, 1.1714, 25.8047, 1, 0, 1, 0, -1, 0, 0, -1, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, -1, -1].$$

The corresponding controller model built in MATLAB/Simulink is presented in 7. Besides, the real-time experiment environment of the MLS testbed is presented in Fig. 8.

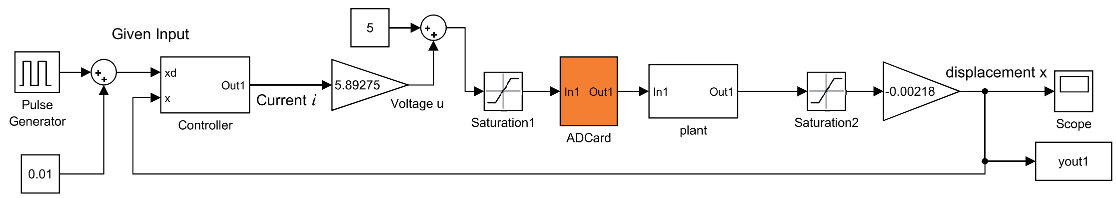


Fig. 6. Simulation diagram of the actual control system of the MLS testbed.

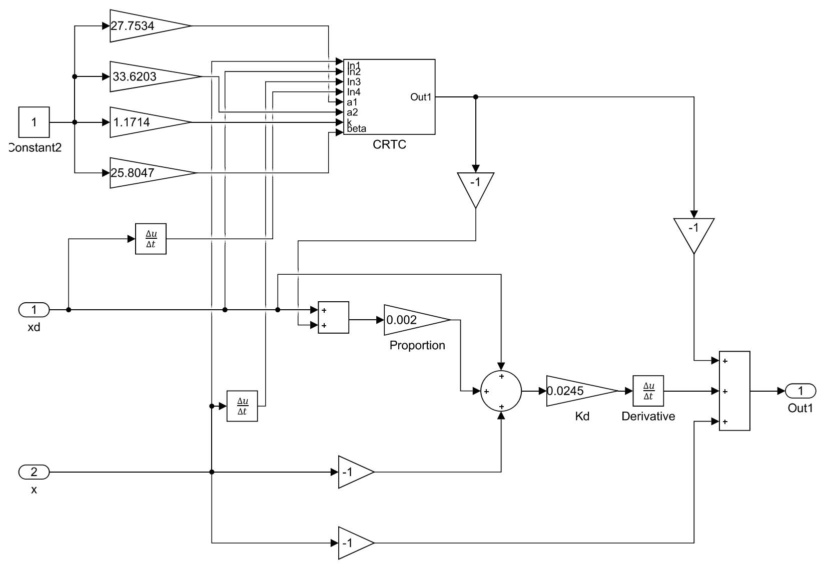


Fig. 7. The controller COSP applied in the MLS testbed.

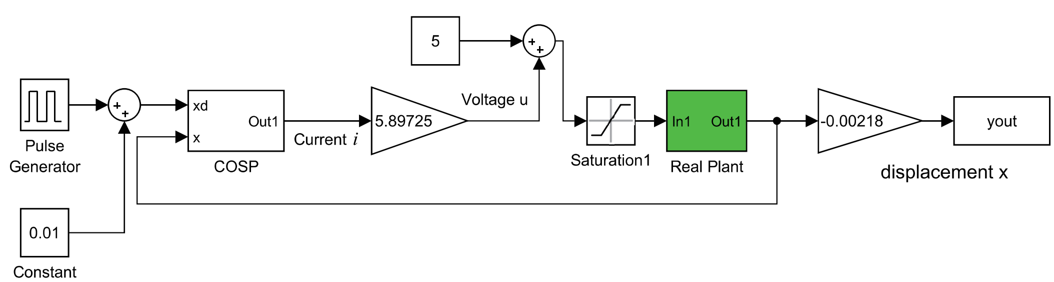


Fig. 8. Experiment environment of the MLS testbed.