

Continuous Preview Control of Dual-Stage Actuator Systems for Reduced Transition Time

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Abstract—Preview Control design is proposed in order to reduce the settling time of Dual-Stage Actuators (DSA’s). It is shown that a significantly better performance is achieved by exploring the extra degree of freedom provided by the secondary actuator before the output transition instant. Given the information of the immediate future reference point, the proposed strategy allows the slow actuator to move ahead of time while the fast actuator maintains the total output at the desired reference. Experimental results demonstrate the effectiveness of the proposed methodology when compared to a conventional form of DSA control design.

I. INTRODUCTION

In this paper we address the issue of reducing the output transition time interval of Dual-Stage Actuators (DSA’s) from an initial reference $\text{ref}(t \leq \tau) = \text{ref}_i$ to a final reference $\text{ref}(t > \tau) = \text{ref}_{i+1}$. The proposed approach makes use of the information on future reference points in order to compute a pair of inputs to be applied before the transition instant ($t = \tau$). This preview control strategy improves the performance of any system that accounts with redundant actuators and prior knowledge of future reference points, and is particularly interesting for systems facing the successive set point scenario.

The class of systems to be considered are Dual-Stage Actuators such as dual-stage Hard-Disk Drives (HDDs) [1]. These systems are defined as two actuators connected in series, a primary (slow) actuator, responsible for providing the system with a long range, and a secondary (fast) actuator, responsible for improving the accuracy and speed of the system. The primary actuator is considered a rigid body of mass M and it is assumed that the friction acting on this actuator (if any) is actively compensated by a friction compensator. The secondary actuator is treated as a body of mass m connected to a spring of constant k with damping c . The secondary actuator is connected in series with the primary and has a range of actuation bounded by $\pm r$ ($r > 0$). Typically, DSA’s have the features that $M \gg m$, $y_1/y_2 \gg 1$, and $|u_2/u_1| \gg m/M$, thus, the coupling forces between the primary and the secondary actuators may be neglected for simplicity.

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In this way, the DSA of interest is modeled as a linear decoupled dual-input single-output (DISO) system, which is represented in a state-space form as:

$$\begin{aligned} \Sigma_1 : \dot{x}_1 &= A_1 x_1 + B_1 u_1, \quad x_1(0) = 0, \quad |u_1| \leq \bar{u}_1 \\ \Sigma_2 : \dot{x}_2 &= A_2 x_2 + B_2 u_2, \quad x_2(0) = 0, \quad |u_2| \leq \bar{u}_2 \\ y &= y_1 + y_2 = C_1 x_1 + C_2 x_2, \end{aligned} \quad (1)$$

where $x_1 = [y_1 \quad \dot{y}_1]^T$ is associated with the primary (coarse) actuator and $x_2 = [y_2 \quad \dot{y}_2]^T$ with the secondary (fine) actuator, and \bar{u}_i is the control saturation level for u_i . Furthermore,

$$\begin{aligned} A_1 &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ b_1 \end{bmatrix}, \quad C_1 = [1 \quad 0], \\ A_2 &= \begin{bmatrix} 0 & 1 \\ a_1 & a_2 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ b_2 \end{bmatrix}, \quad C_2 = [1 \quad 0], \end{aligned}$$

with $a_1 = -k/m$, $a_2 = -c/m$, $b_1 = 1/M$ and $b_2 = 1/m$.

As opposed to DSA control design, a vast number of important achievements regarding settling time reduction can be found in the literature for single stage systems. While Time Optimal Control (TOC) performance is still not achievable without the problems related to chattering and robustness, the past few decades have provided us with a number of controllers that are able to approximate TOC performance. More specifically, an important adaptation of TOC was proposed by Workman [3] under the name of proximate time-optimal servomechanism (PTOS). This control law enables to system to avoid problems related to chattering inasmuch as it only uses the maximal acceleration of the actuator when it is practical to do so: as the system approaches the reference point the controller switches to a linear feedback control gain. More recently, a different approach was presented by Lin *et al.* [4], and then Chen *et al.* [5] where the composite nonlinear feedback (CNF) was developed. This controller is able to achieve an improved performance without increasing the system bandwidth, once it uses dynamic damping to do so. Unfortunately, neither these control strategies are readily adaptable to DSA’s nor make fully use of the redundancy of actuation.

The first attempt to integrate and adapt both the CNF and PTOS to DSA’s was proposed by Zheng *et al.* [6]. This combined controller improves the overall performance of the system while accommodating the saturation of the secondary actuator. The PTOS control law is applied to the primary actuator so that it yields a closed-loop system with a fast rise time and certain allowable overshoot; the CNF control law is applied to the secondary actuator in

order to eliminate the overshoot generated by the primary. Conversely, conventional work on DSA tracking control is based on designing a primary actuator control loop to yield a small or no overshoot, and a secondary actuator controller to follow the position error of the primary [8] and [9]. While the association of PTOS and CNF generates a significantly better performance, both the conventional and the nonlinear strategies do not take into account the possibility of pre-actuation.

Due to the redundancy of actuators, dual-stage systems present liberty of movement outside the transition time interval, i.e., outside the time interval when the system output is moving from one reference point to another. As shown in Fig. 1, we take advantage of this extra degree of freedom provided by the secondary actuator and allow the primary actuator to move ahead of time [7]. The main contribution of the paper is the development of this pre-actuation strategy based on the immediate future reference point in order to reduce the settling time of the system. Moreover, it is shown that the proposed preview control methodology is fully compatible with the nonlinear state-of-art DSA design proposed in [6]. In fact, a continuous switching between both controllers is achieved for the primary actuator. Experimental results demonstrate the effectiveness of the proposed design, which can achieve an improvement of up to 75 % regarding the settling time when compared to a conventional form of DSA control.

As opposed to the problem of pure settling time reduction, the minimum time/energy output-transition problem was already studied in the preview control framework in [10], where a form of pre-actuation is allowed. This technique, however, is not used to solely reduce the settling time of the system and does not consider the saturation of the secondary actuator, which is a hard constraint in the design of fast tracking controllers for DSA's.

To present the proposed methodology, the paper is divided into the following sections: Section II formulates the problem and introduces the general idea, the proposed solution is given in Section III, experimental results are presented in Section IV, and Section V concludes the paper.

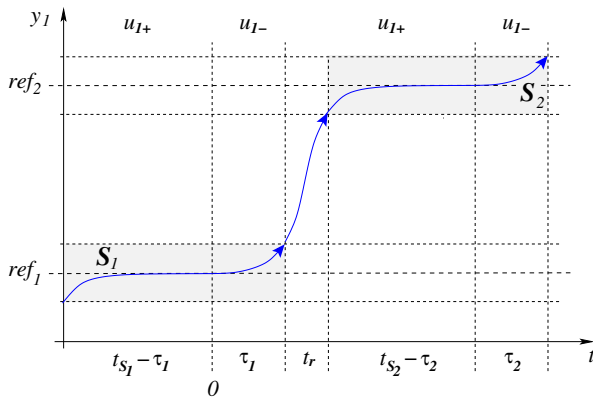


Fig. 1. Schematic representation of the Preview Control Strategy: after t_{S_1} seconds in S_1 , y_1 must move to S_2 with reduced transition time t_r .

II. PROBLEM FORMULATION

An intrinsic characteristic of DSAs is that the coarse and fine actuators are complementary to each other: while the primary actuator is slow and has a large travel range, the secondary actuator is fast but has a limited range of actuation. Due to these complementary characteristics of the DSA it will be assumed that, within the travel range of the secondary actuator, the tracking error of the primary actuator is sufficiently smooth to be compensated with negligible error.

In other words, if we define a manifold S_i ,

$$S_i = \{y_1 \in \mathbb{R} : |y_1 - \text{ref}_i| \leq r\}, \quad (2)$$

where ref_i is the i -th reference point and $\pm r$ is the range of the secondary actuator, then, whenever y_1 is within the manifold S_i , the total output of the system y will be at the i -th reference point with negligible error due to the actions of the secondary actuator. Moreover, if the output y must stay at an initial reference point ref_1 for t_S seconds before moving to another given reference ref_2 , then y_1 must stay in S_1 for t_S seconds before moving to S_2 (Fig. 1).

Therefore, we will address each actuator control design separately as follows.

A. Primary actuator control problem:

For a given initial condition $x_1(0) = [\text{ref}_1 \ 0]^T$, two manifolds S_1 and S_2 determined by (2), and a control saturation level \bar{u}_1 , find a controller

$$|u_1(t)| \leq \bar{u}_1, \quad t \geq 0 \quad (3)$$

and a preview control time $\tau \geq 0$, such that, the output y_1 of the primary actuator is driven from S_1 to S_2 with a reduced transition time t_r , in the following sense:

$$y_1(t) \in S_1, \quad 0 \leq t \leq \tau. \quad (4)$$

$$y_1(t) \in S_2, \quad t \geq \tau + t_r, \quad \text{and} \quad \lim_{t \rightarrow \infty} y_1(t) = \text{ref}_2. \quad (5)$$

■

B. Secondary actuator control problem:

For a control saturation level \bar{u}_2 , find a controller

$$|u_2(t)| \leq \bar{u}_2, \quad t \geq 0 \quad (6)$$

for the secondary actuator to compensate for the error generated by the primary actuator, i.e., to achieve $y = y_1 + y_2 = \text{ref}_i$ when $y_1 \in S_i$.

■

Remark 2.1: Notice that if one chooses $\tau = 0$ one falls in the conventional control strategy for DSA where no preview control is applied. Conversely, there must be an upper bound in the preview control time inasmuch as $t_S - \tau$ must be long enough such that the primary actuator can be driven sufficiently close to the reference before any pre-actuation is applied.

■

III. PROPOSED SOLUTION

In order to solve problem II-A the proposed control strategy will be composed by two different control laws, i.e.,

$$u_1(t) = \begin{cases} u_{1-}(t), & 0 \leq t \leq \tau \\ u_{1+}(t), & t > \tau \end{cases}. \quad (7)$$

In particular, 1) a preview control law, denoted by u_{1-} , will be responsible for the pre-actuation of the system; 2) a nonlinear feedback control law, denoted by u_{1+} , will be applied in order to achieve $y_1 \rightarrow \text{ref}_2$, as $t \rightarrow \infty$. Practically, we can assume that y_1 approaches ref_2 in a short time (not necessarily $t \rightarrow \infty$), say in $\tau_1 + t_r + t_{S_2} - \tau_2$ as denoted in Fig. 1. More specifically, the primary actuator's status becomes $[\text{ref}_2 \ 0]^T$ at this moment. Taking this moment as the new reference time $t = 0$, the proposed controller (7) may apply recursively in a successive step tracking scenario. Problem II-B will be solved by a single composite nonlinear control law that allows the secondary actuator to compensate for the error generated by the primary both during u_{1-} and u_{1+} . Next, we will study the solvability of II-A and II-A respectively with the emphasis on the former.

A. Solvability of II-A

In order to simplify the notation, let us define

$$p := y_1, \quad v := \dot{y}_1,$$

so that $x_1 = [p \ v]^T$ and the primary actuator equation becomes

$$\dot{p} = v, \quad \dot{v} = u_1/M. \quad (8)$$

1) *PTOS Controller u_{1+}* : In literature, e.g., [9], a well known proximate time-optimal servomechanism (PTOS) control is applied to the primary actuator. This is a near time-optimal control strategy that can accommodate plant uncertainty, measurement noise and actuator saturation. The control law is given by:

$$u_{1+}(t) = \text{sat}[\sigma(t)f(\text{ref}_2 - p(t)) - k_2v(t)] \quad (9)$$

where the non-negative continuous function f is defined as

$$f(x) = \begin{cases} k_1|x|, & \text{for } |x| \leq \bar{u}_1/k_1 \\ 2\sqrt{k_1\alpha|x|\bar{u}_1} - \bar{u}_1, & \text{for } |x| > \bar{u}_1/k_1 \end{cases},$$

$\sigma(t) = \text{sgn}(\text{ref}_2 - p(t))$, $0 \leq \alpha \leq 1$ and $\text{sat}(\cdot)$ is with the saturation level of \bar{u}_1 . The constants k_1 and k_2 are positive and they can be designed by any linear control technique, e.g., pole-placement method. The role of the PTOS controller (9) can be summarized as follows for the need of this paper.

Lemma 3.1: For given parameters τ , p_τ , v_τ , ref_2 and S_2 determined by (2), the controller (9) with $t \in [\tau, \infty)$ drives the primary actuator from $x_1(\tau) = [p_\tau \ v_\tau]^T$ into S_2 in the sense of (5). In particular, the transition time t_r is called PTOS-optimized w.r.t. $(v_\tau, \text{ref}_2 - p_\tau)$. ■

The main objective of this paper is to reduce the transition time t_r . Clearly, for a given system and a given PTOS controller, t_r depends on the initial velocity v_τ and the initial step level $\text{ref}_2 - p_\tau$. Without loss of generality, we assume

$\text{ref}_2 > \text{ref}_1$. Roughly speaking, t_r is reduced if v_τ is larger and $\text{ref}_2 - p_\tau$ is smaller. In a conventional control design, the PTOS controller applies with $v_\tau = 0$ and $p_\tau = \text{ref}_1$. In other words, t_r is PTOS-optimized w.r.t. $(0, \text{ref}_2 - \text{ref}_1)$. In this paper, a preview controller is introduced such that t_r is PTOS-optimized w.r.t. $(v_\tau, \text{ref}_2 - \text{ref}_1 - r)$ for some $v_\tau > 0$.

2) *Preview Controller u_{1-}* : The preview control strategy is based on the knowledge that after t_S seconds at ref_1 the total output y will move to ref_2 . As already mentioned in Section II, two manifolds S_1 and S_2 are built around the respective references, and the problem, in the primary actuator perspective, becomes to move from S_1 to S_2 while satisfying the constraints (3) and (4). In order to reduce the transition time from one manifold to another, a pre-actuation will be applied to the primary actuator such that at the transition instant t_S the output y_1 is at the border of S_1 moving toward S_2 (Fig. 1). We assume the preview control time is defined as τ , i.e., the pre-actuation starts τ seconds before the transition instant. In this context, a trajectory must be designed such that the primary actuator changes from a given initial condition $x_1(0) = [p_0 \ 0]^T$ to a desired condition $x_1(\tau) = [p_\tau \ v_\tau]^T$. Specifically, $p_0 = \text{ref}_1$ and $p_\tau = \text{ref}_1 \pm r$ in the present scenario. Among many possible trajectories, the one with a minimum input effort is selected.

Lemma 3.2: For any given $\tau > 0$, p_0 , p_τ , and v_τ , the minimum effort input that takes the primary actuator from the initial condition $x_1(0) = [p_0 \ 0]^T$ to the final condition $x_1(\tau) = [p_\tau \ v_\tau]^T$, is given by:

$$u_{1-}(t) = M(at + b), \quad 0 \leq t \leq \tau \\ a = 6(\tau v_\tau - 2\Delta p)/\tau^3, \quad b = -2(\tau v_\tau - 3\Delta p)/\tau^2 \quad (10)$$

where $\Delta p := p_\tau - p_0$. ■

Proof: This follows from standard calculus of variations in optimal control theory. For a detailed proof please refer to [2].

The controller (10) generates a smooth trajectory for the primary actuator while taking it from initial conditions $x_1(0) = [p_0 \ 0]^T$ to final conditions $x_1(\tau) = [p_\tau \ v_\tau]^T$. This controller, however, does not always satisfy the constraints (3) - (5). Moreover, at the instants $t = 0$ and $t = t_S$ there will be switchings from the PTOS controller (u_{1+}) to preview controller (u_{1-}) and vice versa, which may cause discontinuity in the overall controller (7). Theorem 3.1 shows that with a proper choice of the preview time τ and the final velocity v_τ , the controller (10) not only satisfies the constraints but also provides a continuous switching between the preview controller and the PTOS controller.

Theorem 3.1: For any given $r > 0$, ref_i and S_i determined by (2), $i = 1, 2$, let $\delta := \text{ref}_2 - \text{ref}_1$, $\sigma = \text{sgn}(\delta)$, and $\xi = \delta - \sigma r$, and assume $|\delta| \geq 2r$. Consider a primary actuator with the initial condition $x_1(0) = [\text{ref}_1, 0]$.

- (i) For any τ and v_τ satisfying $\tau > 0$ and $\sigma v_\tau > 0$, the controller (7) composed of (9) and (10) with $p_0 = \text{ref}_1$ and $p_\tau = \text{ref}_1 + \sigma r$ drives the primary actuator from S_1

to \mathbf{S}_2 in the sense of (5). Moreover, the transition time t_r is PTOS-optimized w.r.t. (v_τ, ξ) .

(ii) In (i), if τ and v_τ satisfy

$$\tau v_\tau = 3\sigma r, \quad v_\tau = \sigma \sqrt{\rho \text{sat}(\bar{v}_\tau^2/\rho)} \quad (11)$$

where

$$\bar{v}_\tau = \sqrt{(\rho k_2/2)^2 + \rho f(\xi)} - \rho k_2/2, \quad \rho := 3r/(2M),$$

the controller (7) is continuous over $[0, \infty)$ and the constraints (3) and (4) are satisfied. Thus, the problem II-A is solved. \blacksquare

Proof: (i) During the time interval $[0, \tau)$, Lemma 3.2 shows that the primary actuator is driven by the controller (10) from $x_1(0) = [p_0 \ 0]^\top$ to $x_1(\tau) = [p_\tau \ v_\tau]^\top$. During $[\tau, \infty)$, the initial velocity for the PTOS controller (9) is v_τ and the initial step level is ξ . Obviously, the transition time t_r is PTOS-optimized w.r.t. (v_τ, ξ) by Lemma 3.1.

(ii) Because the first equation of (11) implies $b = 0$ in (10) by noting $p_\tau - p_0 = \sigma r$, the controller (10) becomes $u_{1-}(t) = Mat$ and hence $u_{1-}(0) = 0$.

At the time τ , we have

$$u_{1-}(\tau) = Ma\tau = \sigma v_\tau^2/\rho \quad (12)$$

$$u_{1+}(\tau) = \text{sat}(\sigma f(\xi) - k_2 v_\tau). \quad (13)$$

To show $u_{1+}(\tau) = u_{1-}(\tau)$, we consider two cases.

(a) If $|\xi|$ and hence $f(\xi)$ is large such that $\bar{v}_\tau^2 \geq \rho \bar{u}_1$. From the second equation of (11), we have $v_\tau = \sigma \sqrt{\rho \bar{u}_1}$. As a result, on one hand, (12) gives

$$u_{1-}(\tau) = \sigma \bar{u}_1;$$

on the other hand, (13) gives

$$u_{1+}(\tau) = \sigma \text{sat}(f(\xi) - k_2 \sqrt{\rho \bar{u}_1}).$$

It suffices to show

$$f(\xi) - k_2 \sqrt{\rho \bar{u}_1} \geq \bar{u}_1 \quad (14)$$

to prove $u_{1+}(\tau) = u_{1-}(\tau)$. Indeed, $\bar{v}_\tau \geq \sqrt{\rho \bar{u}_1}$ gives

$$\sqrt{(\rho k_2/2)^2 + \rho f(\xi)} \geq \rho k_2/2 + \sqrt{\rho \bar{u}_1}$$

and hence (14).

(b) If $|\xi|$ and hence $f(\xi)$ is small such that $\bar{v}_\tau^2 < \rho \bar{u}_1$. From the second equation of (11), we have $v_\tau = \sigma \bar{v}_\tau$. Then, (12) gives

$$u_{1-}(\tau) = \sigma \bar{v}_\tau^2/\rho,$$

and (13) gives

$$u_{1+}(\tau) = \sigma \text{sat}(f(\xi) - k_2 \bar{v}_\tau).$$

It suffices to show

$$f(\xi) - k_2 \bar{v}_\tau = \bar{v}_\tau^2/\rho < \bar{u}_1$$

to prove $u_{1+}(\tau) = u_{1-}(\tau)$. Indeed, the equation holds from the definition of \bar{v}_τ and the inequality from the assumption directly.

From above, we have proven $u_{1-}(0) = 0$ and $u_{1+}(\tau) = u_{1-}(\tau)$, i.e., the controller (7) is continuous over $[0, \infty)$.

Next, notice that the control law (10) is monotonic ($b = 0$) and $v(0) = 0$, then y_1 moves from $y_1(0) = \text{ref}_1$ to $y_1(\tau) = \text{ref}_1 + \sigma r$ monotonically. Therefore, the constraint (4) is satisfied.

Finally, by noting $v_\tau^2 \leq \rho \bar{u}_1$ from the second equation of (11), we have

$$|u_{1-}(t)| = |Mat| \leq |Ma\tau| = v_\tau^2/\rho \leq \bar{u}_1$$

which proves the constraint (3). The proof is thus complete. \square

In Theorem 3.1, we assume $|\delta| \geq 2r$ (or, $|\xi| \geq r$) which means that the two manifold \mathbf{S}_1 and \mathbf{S}_2 do not overlap. When $|\delta| < 2r$ (or, $|\xi| < r$), the controller in Theorem 3.1 may not work directly because a small $|\xi|$ gives a small $f(\xi)$ and hence a small \bar{v}_τ which implies a large τ . In particular, when $|\delta| = r$, we have $\xi = 0$ and $\tau = \infty$. However, τ should be small enough such that $t_S - \tau$ is sufficient for the previous PTOS to settle down. Nevertheless, the controller in Theorem 3.1 still works with a slight modification by resetting a smaller $r = |\delta|/2$. With this modification, we will show that there is an upper boundary for τ , which is independent of r , ref_1 , and ref_2 . The result is given below.

Corollary 3.1: For a given \bar{r} and any $r \in (0, \bar{r}]$, the preview control time τ set in Theorem 3.1-(ii) has an upper boundary, i.e., $\tau \leq \bar{\tau}$, where $\bar{\tau}$ is independent of r , ref_1 , and ref_2 . In particular,

$$\bar{\tau} = 3/\min\{\sqrt{\bar{\rho}\bar{u}_1/\bar{r}}, \sqrt{(\bar{\rho}k_2/2)^2 + \bar{\rho}\bar{k}_1 - \bar{\rho}k_2/2}\} \\ \bar{\rho} = 3/(2M), \quad \bar{k}_1 = \min\{k_1, \bar{u}_1/\bar{r}\}.$$

Proof: In Theorem 3.1, we assume $|\delta| \geq 2r$ which implies $|\xi| \geq r$. From the definitions of f and \bar{k}_1 , we have

$$f(\xi)/r \geq f(r)/r \geq \bar{k}_1. \quad (15)$$

Since the equations (11) give $\tau = 3/\sqrt{(\bar{\rho}/r)\text{sat}(\bar{v}_\tau^2/(\bar{\rho}r))}$, it suffices to prove

$$\sqrt{(\bar{\rho}/r)\text{sat}(\bar{v}_\tau^2/(\bar{\rho}r))} \geq \min\{\sqrt{\bar{\rho}\bar{u}_1/\bar{r}}, \sqrt{(\bar{\rho}k_2/2)^2 + \bar{\rho}\bar{k}_1 - \bar{\rho}k_2/2}\}. \quad (16)$$

If $\bar{v}_\tau^2/(\bar{\rho}r) \geq \bar{u}_1$, the inequality (16) holds obviously. Otherwise, we have

$$\text{lhs} = \bar{v}_\tau/r = \sqrt{(\bar{\rho}k_2/2)^2 + \bar{\rho}f(\xi)/r - \bar{\rho}k_2/2} \geq \text{rhs}$$

using (15). The proof is thus complete. \square

B. Solvability of II-B

The secondary actuator controller is a form of Composite Nonlinear Feedback (CNF) borrowed from [6]. Its control law is given by:

$$u_2 = u_{2L} + u_{2N} \quad (17)$$

where u_{2L} is a linear feedback law which stabilizes the secondary actuator with a higher bandwidth than that of

the primary, and u_{2N} is a nonlinear feedback law which improves the performance of the overall DSA system. The linear controller is given by standard state feedback gain,

$$u_{2L} = Wx_2, \quad (18)$$

where $W = [w_1 \ w_2]$ may be calculated by any linear control technique. The nonlinear feedback controller is given by:

$$u_{2N} = \gamma(\text{ref}_2, y)H \begin{bmatrix} p - \text{ref}_2 \\ v \end{bmatrix} \quad (19)$$

where H is chosen as:

$$H = \frac{1}{b_2} [(a_1 + b_2w_1 + b_1k_1) \quad (a_2 + b_2w_2 + b_1k_2)], \quad (20)$$

with constants k_1 and k_2 from (9), and the nonlinear function $\gamma(\cdot)$ is:

$$\gamma(\text{ref}_2, y) = e^{-\beta|\text{ref}_2 - y|}, \quad (21)$$

where β is a tuning parameter.

Due to the proper choice of H and $\gamma(\text{ref}_2, y)$, the DSA closed-loop dynamics change from the primary to the secondary actuator control loop as the system approaches the reference point. This transition results in an improved performance inasmuch as the secondary actuator is designed to have a high bandwidth and a small damping ratio, allowing it to compensate the overshoot generated by the primary actuator [6]. Therefore, for the DSA system in (1) with the primary actuator under the control law (7), the secondary actuator under the nonlinear control law (17) is able to compensate for the error generated by the primary actuator under constraint (6), i.e., problem II-B is solved.

IV. EXPERIMENTAL RESULTS

The proposed control scheme was implemented in the experimental DSA setup in [6]. The system is comprised of a linear motor (LM) as the primary stage and a piezo actuator (PZT) as the secondary stage. The LM has a 0.5 m travel range and a $1\mu\text{m}$ resolution glass scale encoder. The PZT has a maximum travel range of $\pm 15\mu\text{m}$ and an integrated capacitive position sensor with 0.2 nm resolution to measure the relative displacement between the LM and the PZT. The resonance of the PZT is actively damped by its integrated control electronics.

In order to compensate for the friction present in the LM, a model-based friction compensator was employed [11]. Thus, the primary actuator is modeled as a double integrator and the DSA is fully described by the set of equations in (1). For this particular system $\bar{u}_1 = 1\text{ V}$ and $\bar{u}_2 = 5\text{ V}$, and the parameters a_1 , a_2 , b_1 and b_2 were identified experimentally and are given by

$$\begin{aligned} a_1 &= -10^6, & b_1 &= 1.5 \times 10^7, \\ a_2 &= -1810, & b_2 &= 3 \times 10^6. \end{aligned} \quad (22)$$

When working in its linear region, the PTOS control law becomes a linear feedback gain $K = [k_1 \ k_2]$ which may be parameterized as,

$$K = \frac{1}{b_1} [(2\pi\omega_1)^2 \quad 4\pi\omega_1\zeta_1] \quad (23)$$

with ω_1 and ζ_1 the natural frequency and damping ratio of the primary actuator closed-loop system. By pushing $\omega_1 = 30\text{ Hz}$, the PTOS linear region is given by $|\text{ref}_2 - p(t)| \leq 422\mu\text{m}$. Similarly, the PZT gain is calculated by choosing $\omega_2 = 300\text{ Hz}$. The gains are given by,

$$\begin{aligned} K &= 10^{-3} \times [2.4 \quad 0.0225], \\ W &= -[0.8385 \quad 0.0005], \\ H &= -[1.1602 \quad 0.001]. \end{aligned} \quad (24)$$

In the nonlinear function (21) the free parameter is chosen as $\beta = 0.001$.

In order to add robustness to the preview control strategy, the feedback/feedforward scheme in Fig. 2 was implemented. The preview control input u_{1-} is applied to an internal reference model, from which the desired trajectory \hat{x}_I is obtained. Then, this trajectory is tracked by applying the designed preview input as a feedforward reference and by stabilizing the system with a linear feedback gain $Q = [q_1 \ q_2]$, which may be computed by a standard linear control technique.

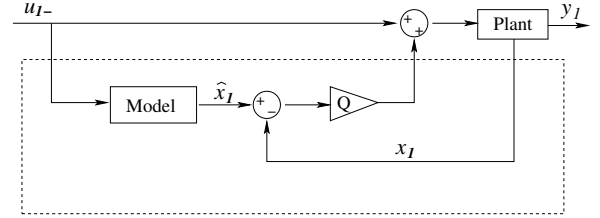


Fig. 2. Preview control strategy implemented in the primary actuator. A feedforward/feedback scheme is used in order to add robustness to the controller.

Three forms of DSA control strategy were compared in the experimental setup: (a) a conventional form of DSA control, where the primary actuator is tuned to have no overshoot [12]; (b) the nonlinear feedback control without pre-actuation, where the primary actuator is allowed to present some overshoot for improved performance [6]; and (c) the proposed preview control strategy. In order to implement controllers (a) and (b), different values of ζ_1 in (23) were chosen accordingly. All controllers were implemented by a DSP system (dSPACE-DS1103) with the sampling frequency of 5 kHz, and settling time was defined as the time it takes for the total position output y to enter and remain within $\pm 2\mu\text{m}$ relative to the setpoint.

Figures 3 and 4 show the step responses for references of $30\mu\text{m}$ and $100\mu\text{m}$, respectively. The top plot (a) shows the conventional control, the middle plot (b) shows the nonlinear feedback without pre-actuation, and the bottom plot (c) shows the proposed preview controller. In those plots the thick line is the total output of the system (y), the dashed line is the primary actuator output (y_1), and the dash-dotted line is the secondary actuator output (y_2). The $30\mu\text{m}$ ($100\mu\text{m}$) comparative improvement is of 83% (81%) over a single stage actuator; 75% (70%) over controller (a) and 70% (64%) over controller (b). Fig. 5 shows the response of the three different controllers for the successive set point

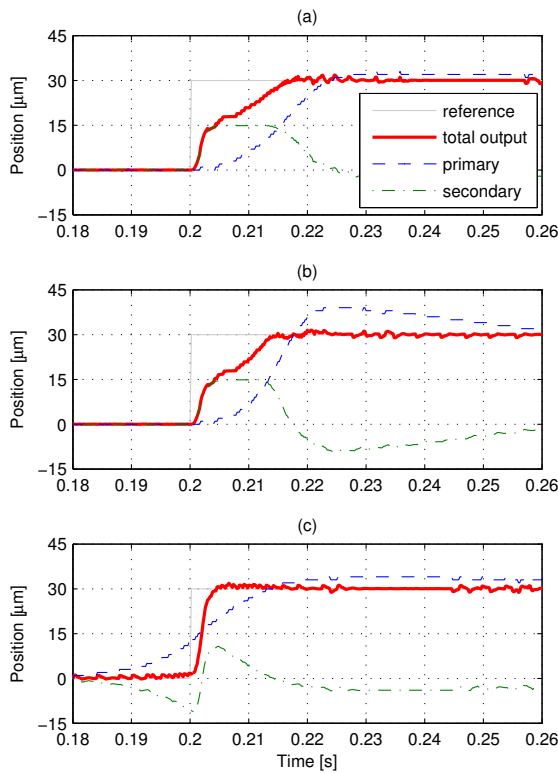


Fig. 3. Responses for a $30\ \mu\text{m}$ step reference, the proposed control design (c) has a settling time of 3.8 ms and a preview control time of 20.0 ms.

scenario. These plots demonstrate the effectiveness of the proposed design.

V. CONCLUSION

A form of preview control for DSA systems was presented in this paper. Based on the information of future reference points, a control strategy was developed so that inputs were applied before the transition time interval. This control strategy takes full advantage of the redundancy of actuators enabling the DSA system to achieve an improved performance. Experimental results showed the effectiveness of the proposed approach which is able to significantly reduce the settling time of the overall DSA system.

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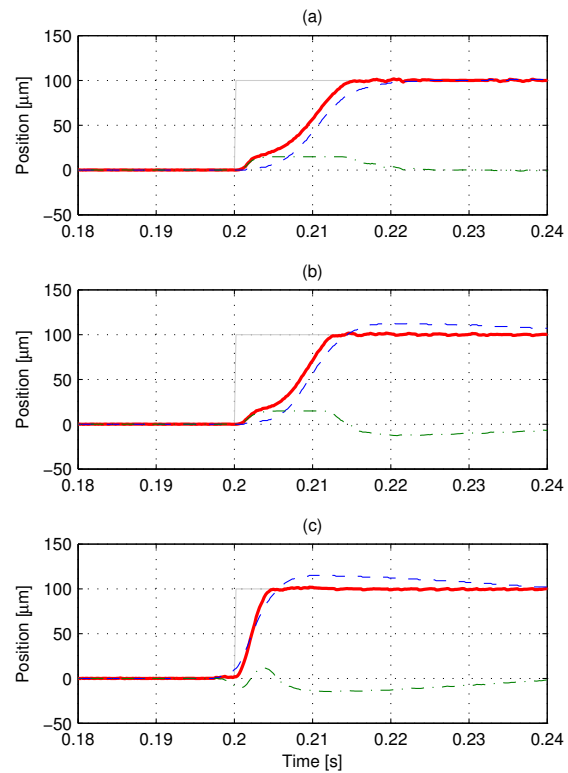


Fig. 4. Responses for a $100\ \mu\text{m}$ step reference, the proposed control design (c) has a settling time of 4.4 ms and a preview control time of 7.8 ms.

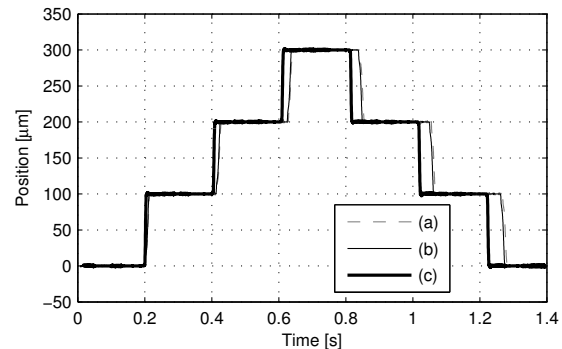


Fig. 5. Staircase response for the three different controllers. Here only the total output y is depicted.

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