2020-01

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IEEE

Sands, Tim, Jae Jun Kim, and Brij N. Agrawal. "Improved Hamiltonian adaptive control of spacecraft."2009 IEEE Aerospace conference. IEEE, 2009.
http://hdl.handle.net/10945/70959

Improved Hamiltonian Adaptive Control of Spacecraft

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Abstract—Spacecraft control is complicated by on-orbit inertia uncertainties. Considerable initial, on-orbit check-out time is required for identification of accurate system models enabling fine pointing. Smart, plug-n-play control algorithms should formulate smart control signals regardless of inertia. Adaptive control techniques provide such promise. Spacecraft control has been proposed to be adapted in the inertial frame based on estimated inertia to minimize tracking error. Due to unwieldy computations, later researchers suggested adapting the control in the body frame. This paper derives this later suggested approach using the recommended 9-parameter regression model for 3-axis spacecraft rotational maneuvers. Additionally, a new 6-parameter regression model is shown to be equivalent. A new, further-reduced 3-parameter regression model is demonstrated to yield similar performance. A new improved, simplified adaptive feedforward technique is developed and shown to provide superior performance. Following promising simulations, experimental verification is performed on a free-floating three-axis spacecraft simulator actuated by non-redundant, single-gimbaled control moment gyroscopes.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. ADAPTIVE FEEDFORWARD DEVELOPMENT 2
3. REGRESSION MODELING 3
4. 6-PARAMETER REGRESSION 4
5. 3-PARAMETER REGRESSION 4
6. SIMULATIONS 4
7. EXPERIMENTAL VERIFICATION 8
8. CONCLUSIONS 9
REFERENCES 9
BIOGRAPHY 9

1. INTRODUCTION

Adaptive control techniques often adapt control commands based upon errors tracking trajectories and/or estimation errors. *Direct* adaptive control techniques typically directly adapt the control signal without translation of estimated parameters. *Indirect* adaptive control techniques indirectly adapt the control signal by translating the estimates of unknown system parameters to formulate a control signal. The adaptation rule is derived using a proof that demonstrates the elimination of tracking errors (the true objective) and demonstrates stability, which is complicated by the nonlinear closed loop system. Two fields of application of adaptive control are robotic manipulators and spacecraft maneuvers utilizing either direct or indirect adaptive approaches [1], [2], [3].

Feedforward controls attempt to exactly mimic the plant dynamics to provide zero-lag trajectory tracking which requires knowledge of the spacecraft plant's inertia. Feedback controls add robustness by generating torque commands based on tracking errors, but suffer from lag since the tracking errors must have already been experienced.

While some adaptive techniques concentrate on adaptation of the feedback control, others have been suggested to modify a feedforward control command. E.H. Anderson [4] evaluated the filtered-x LMS algorithm with FIR estimation for adapting the feedforward command signals. Simpler adaption rules have been used for adaptation of the feedforward signal in the inertial reference frame [5], [6], [7]. While the adaptation is simpler in general form, the resulting regression model used in the control signal requires several pages to express for three-dimensional spacecraft rotational maneuvers. Other references also utilizing the inertial frame [6], [8] have been extended to include attitude control system power tracking in the control signal [8], but still suffer from the algorithmic complexity that accompanies the inertial frame. The measured regression matrix is required in the control calculation, so this approach is computationally inappropriate for spacecraft rotational maneuvers motivating further study. Subsequently, Slotine's 9-parameter estimation general approach [6] was suggested for implementation in the body reference frame by Fossen [9] as displayed in Fig 1. The method was derived for *slip translation* of the space shuttle, but neither simulated nor experimentally verified. Nonetheless, this method appears promising for practical implementation for three-dimensional spacecraft *rotational maneuvers*. This paper derives the Slotine-Fossen approach for 3-dimensional

978-1-4244-2622-5/09/$25.00 ©2009 IEEE
IEEEAC paper #1638, Version 2.0, Updated December 4, 2008

spacecraft rotational maneuvers (Eqn. 20). An alternative approach utilizing non-adaptive feedback, while retaining adaptive feedforward is demonstrated to increase performance (Fig 2). Estimation requirements are reduced with a new six-parameter regression model (Eqn. 25) and also a new three-parameter regression model (Eqn. 26). After simulations provide promise, experiments verify the effectiveness of the suggested approaches and resultant performance enhancements.

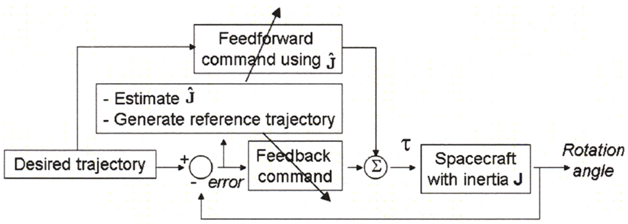


Fig 1 Slotine/Fossen Adaptive control relationships

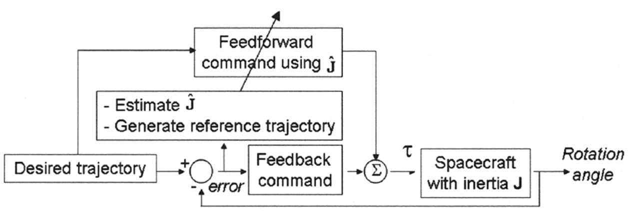


Fig 2 Proposed Adaptive control relationships

The suggested algorithms may be plugged in place of any attitude control algorithm based on state feedback (angular position and velocity) to achieve the demonstrated performance increase. Since spacecraft already use angular position and velocity measurements in typical control methods (including proportional-derivative, PD control); implementation is quite easy. Input the feedforward and PD-feedback controllers with a reference trajectory and adapt the feedforward signal using a simple adaption rule that is proven to be stable and eliminate tracking errors.

2. ADAPTIVE FEEDFORWARD DEVELOPMENT

After defining requisite quantities, Lyapunov stability analysis yields a stable and convergence adaptive feedforward control design with PD feedback control. First define the ideal feedforward control, u_{ff} from the dynamics. If the dynamics were exactly known, they would determine the feedforward control that would accomplish a desired maneuver $\{\ddot{q}_d\}$ in general body coordinates with no error. Later, specific body coordinates ϕ, θ, ψ will be used for roll, pitch, and yaw respectively. Noting that (^) is used for estimates and (˙) is used for time-derivative, the equations of motion for inertia matrix [**J**], Coriolis matrix [**C**], and applied external torque τ are:

$$[\mathbf{J}]\{\ddot{\mathbf{q}}\}+[\mathbf{C}]\{\dot{\mathbf{q}}\}=\{\boldsymbol{\tau}\} \quad (1)$$

for $\mathbf{J}=\mathbf{J}^T>0$, $\dot{\mathbf{J}}=0$, $\mathbf{C}$=skew symmetric

Define:

$$[\mathbf{J}]\{\ddot{\mathbf{q}}\}+[\mathbf{C}]\{\dot{\mathbf{q}}\}=\{\boldsymbol{\tau}\}_{ideal}=[\mathbf{J}]\{\ddot{\mathbf{q}}_d\}+[\mathbf{C}]\{\dot{\mathbf{q}}_d\}$$

$$[\mathrm{J}]\{\ddot{\mathrm{q}}_d\}+[\mathrm{C}]\{\dot{\mathrm{q}}_d\}=\{\Phi\}[\Theta]=\{u_{ff}\}_{ideal} \quad (2)$$

Define the tracking errors using tilda (˜): $\tilde{\mathbf{q}}=\mathbf{q}-\mathbf{q}_d$

Thus $\dot{\tilde{\mathbf{q}}}=\dot{\mathbf{q}}-\dot{\mathbf{q}}_d$ and $\ddot{\tilde{\mathbf{q}}}=\ddot{\mathbf{q}}-\ddot{\mathbf{q}}_d$ (3)

Allowing definition of the reference trajectory for λ>0

$$\ddot{\mathbf{q}}_r=\ddot{\mathbf{q}}_d-\lambda\underbrace{(\dot{\mathbf{q}}-\dot{\mathbf{q}}_d)}_{\dot{\tilde{\mathbf{q}}}}=\ddot{\mathbf{q}}_d-\lambda(\dot{\tilde{\mathbf{q}}}) \quad (4)$$

and $$\dot{\mathbf{q}}_r=\dot{\mathbf{q}}_d-\lambda\underbrace{(\mathbf{q}-\mathbf{q}_d)}_{\tilde{\mathbf{q}}}=\dot{\mathbf{q}}_d-\lambda(\tilde{\mathbf{q}}) \quad (5)$$

Define a combined measure of tracking error (error tracking the reference trajectory):

$$s=\dot{\mathbf{q}}-\dot{\mathbf{q}}_r=(\dot{\mathbf{q}}-\dot{\mathbf{q}}_d)+\lambda(\mathbf{q}-\mathbf{q}_d)=\dot{\tilde{\mathbf{q}}}+\lambda\tilde{\mathbf{q}} \quad (6)$$

$$\dot{s}=\ddot{\mathbf{q}}-\ddot{\mathbf{q}}_r=(\ddot{\mathbf{q}}-\ddot{\mathbf{q}}_d)+\lambda(\dot{\mathbf{q}}-\dot{\mathbf{q}}_d)=\ddot{\tilde{\mathbf{q}}}+\lambda\dot{\tilde{\mathbf{q}}} \quad (7)$$

From our earlier regression definition (equation (2)) of the feedforward control, define:

$$\Theta=\begin{Bmatrix}J_{xx} & J_{xy} & J_{xz} & J_{yy} & J_{yz} & J_{zz}\end{Bmatrix}^T \quad (8)$$

where $\dot{\Theta}=0$ for time-invariant inertia,

$$\hat{\Theta}=\begin{Bmatrix}\hat{J}_{xx} & \hat{J}_{xy} & \hat{J}_{xz} & \hat{J}_{yy} & \hat{J}_{yz} & \hat{J}_{zz}\end{Bmatrix}^T \quad (9)$$

Thus, the estimated dynamics may be defined using a similar regression similar in form to the actual dynamics:

$$[\hat{\mathbf{J}}]\{\ddot{\mathbf{q}}_r\}+[\hat{\mathbf{C}}]\{\dot{\mathbf{q}}_r\}=[\Phi_r(\ddot{\mathbf{q}}_r,\dot{\mathbf{q}}_r)]\{\hat{\Theta}\} \quad (10)$$

Define the estimation error as the difference between estimated and actual inertia:

$$\tilde{\Theta}=\hat{\Theta}-\Theta \quad (11)$$

Consider the candidate Lyapunov function where $\mathbf{K}_p$ and $\mathbf{K}_d$ are proportional and derivative control gains respectively:

$$V = \frac{1}{2}\mathbf{s}^T\mathbf{J}\mathbf{s} + \frac{1}{2}\tilde{\Theta}^T\Gamma^{-1}\tilde{\Theta} + \frac{1}{2}\tilde{\mathbf{q}}^T\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)\tilde{\mathbf{q}} \quad (12)$$

Differentiating:

$$\dot{V} = \mathbf{s}^T\mathbf{J}\dot{\mathbf{s}} + \dot{\tilde{\Theta}}^T\Gamma^{-1}\tilde{\Theta} + \dot{\tilde{\mathbf{q}}}^T\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)\tilde{\mathbf{q}} \quad (13)$$

Substitute for $\dot{s}$, distribute [**J**], substitute for $\mathbf{J}\ddot{\mathbf{q}}$ and add & subtract $\mathbf{C}\dot{\mathbf{q}}_r$ grouping $\Phi_r\Theta$. Then reverse distribute [**C**] and substitute $\dot{\mathbf{q}} - \dot{\mathbf{q}}_r$ for **s**. Use skew symmetry to reduce:

$$\dot{V} = \mathbf{s}^T\left(\tau - \mathbf{J}\ddot{\mathbf{q}}_r - \mathbf{C}\dot{\mathbf{q}}_r\right) + \dot{\tilde{\Theta}}^T\Gamma^{-1}\tilde{\Theta} + \dot{\tilde{\mathbf{q}}}^T\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)\tilde{\mathbf{q}} \quad (14)$$

Note Fig 2 and let torque $\boxed{\tau = \Phi_r\hat{\Theta} - \mathbf{K}_d\dot{\tilde{\mathbf{q}}} - \mathbf{K}_p\tilde{\mathbf{q}}}$ (15)

Group $\Phi_r\tilde{\Theta}$ and equate $\dot{\tilde{\Theta}} = \dot{\hat{\Theta}}$:

$$\dot{V} = \mathbf{s}^T\left(\Phi_r\tilde{\Theta} - \mathbf{K}_d\dot{\tilde{\mathbf{q}}} - \mathbf{K}_p\tilde{\mathbf{q}}\right) + \dot{\hat{\Theta}}^T\Gamma^{-1}\tilde{\Theta} + \dot{\tilde{\mathbf{q}}}^T\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)\tilde{\mathbf{q}} \quad (16)$$

Using the combined measure of tracking error define

$$\boxed{\dot{\hat{\Theta}}^T = -\mathbf{s}^T\Phi_r\Gamma \quad \Gamma > 0} \quad (17)$$

Cancel $\Phi_r\tilde{\Theta}$ and substitute for $\mathbf{s}^T$ then distribute $(\dot{\tilde{\mathbf{q}}} + \lambda\tilde{\mathbf{q}})^T$ twice. Group terms then reverse distribute to $\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)$ canceling $\left(\lambda\mathbf{K}_d + \mathbf{K}_p\right)$ terms.

$$\dot{V} = -\dot{\tilde{\mathbf{q}}}^T\mathbf{K}_d\dot{\tilde{\mathbf{q}}} - \lambda\tilde{\mathbf{q}}^T\mathbf{K}_p\tilde{\mathbf{q}} \le 0 \quad (18)$$

For negative semi-definite Lyapunov function derivative, Barbalat's lemma says: *if the differential function V(t) has a finite limit as t→∞ (bounded) and is such that $\ddot{V}(t)$ exists and is bounded, then $\dot{V}(t)\rightarrow 0$ as t→∞.* V(t) is lower bounded and $\dot{V}(t)$ is negative semi-definite, so if $\dot{V}(t)$ is uniformly continuous in time, then $\dot{V}(t)\rightarrow 0$ as t→∞. To confirm uniform continuity, differentiate: $\ddot{\tilde{\mathbf{q}}} = \ddot{\mathbf{q}} - \ddot{\mathbf{q}}_d$ and $\ddot{V} = -2\ddot{\tilde{\mathbf{q}}}^T\mathbf{K}_d\dot{\tilde{\mathbf{q}}} - \lambda\dot{\tilde{\mathbf{q}}}^T\mathbf{K}_p\tilde{\mathbf{q}}$. Since $V(t) < V(0)\forall t > 0$, $V(t) = V(\mathbf{s}, \dot{\tilde{\mathbf{q}}}, \tilde{\mathbf{q}}, \tilde{\Theta})$ is bounded, thus $\mathbf{s}, \dot{\tilde{\mathbf{q}}}, \tilde{\mathbf{q}}$, and $\tilde{\Theta}$ are all bounded. Since $\tilde{\mathbf{q}} = \mathbf{q} - \mathbf{q}_d$ and $\dot{\tilde{\mathbf{q}}} = \dot{\mathbf{q}} - \dot{\mathbf{q}}_d$ are bounded, and $\dot{\mathbf{q}}_d$ & $\mathbf{q}_d$ are bounded inputs, $\mathbf{q}$ and $\dot{\mathbf{q}}$ are bounded, thus, $\dot{\mathbf{q}}_r$ is bounded. Also, since $\ddot{\mathbf{q}}_d$ is a bounded input, $\ddot{\mathbf{q}}_r$ is bounded. Additionally, since $\tilde{\Theta} = \hat{\Theta} - \Theta$ is bounded, and Θ is a bounded, real world system (no such system of infinite inertia), $\hat{\Theta}$ is bounded, thus $\boldsymbol{\tau}(\hat{\Theta}, \mathbf{q}_r, \dot{\mathbf{q}}_r)$ is bounded. Recalling the Newton-Euler relation (equation (1)) and our defined torque (noting we have just demonstrated $\boldsymbol{\tau}(\hat{\Theta}, \mathbf{q}_r, \dot{\mathbf{q}}_r)$ and $\dot{\mathbf{q}}$ are bounded), $\ddot{\mathbf{q}}$ must be bounded.

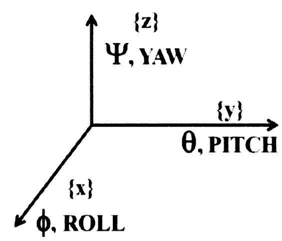
$$[\mathbf{J}]\{\ddot{\mathbf{q}}\} + [\mathbf{C}]\{\dot{\mathbf{q}}\} = \boldsymbol{\tau}(\hat{\Theta}, \mathbf{q}_r, \dot{\mathbf{q}}_r) \rightarrow \{\ddot{\mathbf{q}}\} = [\mathbf{J}]^{-1}\left[\boldsymbol{\tau}(\hat{\Theta}, \mathbf{q}_r, \dot{\mathbf{q}}_r) - [\mathbf{C}]\{\dot{\mathbf{q}}\}\right] \quad (19)$$

Since $\ddot{V}$ is bounded, $\dot{V}$ is uniformly continuous. By Barbalat's lemma: $\dot{V} = -\dot{\tilde{\mathbf{q}}}^T\mathbf{K}_d\dot{\tilde{\mathbf{q}}} - \lambda\tilde{\mathbf{q}}^T\mathbf{K}_p\tilde{\mathbf{q}} \rightarrow 0 \text{ as } t \rightarrow \infty$.

$$\dot{\tilde{\mathbf{q}}}, \tilde{\mathbf{q}} \rightarrow 0 \text{ as } t \rightarrow \infty$$

3. REGRESSION MODELING

Feedforward control utilizes Newton-Euler equations of rotational motion to derive a control command that would be perfect in a perfect world. Typically feedback control accounts for non-perfections (e.g. modeling errors, noise, etc.). The equations of motion may be written as a regression model to facilitate easy expression as matrix equations.



For specific body coordinates (ϕ, θ, ψ) The general velocity is the angular velocity, or $\dot{\mathbf{q}} = \boldsymbol{\omega}$. The dynamics may be written as a regression model in terms of the reference trajectory as done in Slotine/Fossen for *slip translation* of the Space Shuttle. The result for 3D spacecraft *rotational maneuvers* is a 9-parameter, highly nonlinear expression for the feedforward control.

$$\left[\Phi(\omega_r, \dot{\omega}_r)\right]_{3x9}\{\Theta\}_{9x1} = \quad (20)$$

$$\begin{bmatrix} \dot{\omega}_x & \dot{\omega}_y & \dot{\omega}_z & 0 & 0 & 0 & 0 & -\omega_z & \omega_y \\ 0 & \dot{\omega}_x & 0 & \dot{\omega}_y & \dot{\omega}_z & 0 & \omega_z & 0 & \omega_x \\ 0 & 0 & \dot{\omega}_x & 0 & \dot{\omega}_y & \dot{\omega}_z & -\omega_y & \omega_x & 0 \end{bmatrix}_r \begin{Bmatrix} J_{xx} \\ J_{xy} \\ J_{xz} \\ J_{yy} \\ J_{yz} \\ J_{zz} \\ H_x \\ H_y \\ H_z \end{Bmatrix}$$

These dynamics establish the feedforward command when the inertia is known and correct. Accordingly, utilize the *estimated* dynamics for formulate the adapted feedforward command based on estimated inertia and the reference trajectory.

$$\left[\Phi(\omega_r, \dot{\omega}_r)\right]\{\Theta\} = \left[\Phi_r\right]\{\hat{\Theta}\} + error \quad (21)$$

Additionally, feedback control is added utilizing the reference trajectory in PD control architecture. Slotine/Fossen utilizes the reference trajectory for feedback resulting in the following eqn. (22):

$$u_{fb} = -K_d \mathbf{s} = -K_d(\dot{q} - \dot{q}_r) = -K_d(\dot{q} - \dot{q}_d - \lambda(\dot{q} - \dot{q}_d))$$

Notice this definition of feedback control defines the reference trajectory gain $\lambda = K_p / K_d$. Thus choice of K_p and K_d constrains/defines the reference trajectory (in the feedforward also).

$$u_{fb} = K_d(\dot{q} - \dot{q}_d) - \underbrace{\lambda K_d}_{K_p}(\dot{q} - \dot{q}_d) \tag{23}$$

Similar to the example in [7], adaptive *feedforward* techniques in this study are compared by fixing feedback gains: $K_d = 200$, $\lambda = 1/2 \rightarrow K_p = 100$. Each approach compared will have identical adaptive feedback controls. It is proposed here to maintain PD feedback control based on the *desired* trajectory rather than the reference:

$$\tau = \underbrace{[\Phi]\{\hat{\Theta}\}}_{u_{ff}} - \underbrace{K_d(\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) - K_p(\mathbf{q} - \mathbf{q}_d)}_{u_{fb}} \tag{24}$$

4. 6-PARAMETER REGRESSION

Recalling the definition of angular momentum $\{\mathbf{H}\}=[\mathbf{J}]\{\omega\}$, substitution into the 9-parameter Slotine/Fossen regression model allows reformulation into the following, equivalent 6-parameter regression model resulting in considerable simplification (while remaining a highly nonlinear feedforward control).

$$\left[\Phi(\omega_r, \dot{\omega}_r)\right]_{3x6} \{\hat{\Theta}\}_{6x1} = \begin{bmatrix} \dot{\omega}_x & \dot{\omega}_y & \dot{\omega}_z & -\omega_y\omega_z & 0 & \omega_z\omega_y \\ \omega_x\omega_z & \dot{\omega}_x & 0 & \dot{\omega}_y & \dot{\omega}_z & -\omega_z\omega_x \\ -\omega_x\omega_y & 0 & \dot{\omega}_x & \omega_y\omega_x & \dot{\omega}_y & \dot{\omega}_z \end{bmatrix}_r \begin{Bmatrix} \hat{J}_{xx} \\ \hat{J}_{xy} \\ \hat{J}_{xz} \\ \hat{J}_{yy} \\ \hat{J}_{yz} \\ \hat{J}_{zz} \end{Bmatrix}$$

Equation (25): Reduced-order 6-parameter feedforward

Utilizing reference feedback, this reduced form is equivalent to Slotine/Fossen's 9-parameter estimation version and is referred to as *Derived6* to denote the heritage from Slotine/Fossen, yet still indicate the alteration to a reduced form. The first proposed adaptive technique (*Proposed6*) utilizes this regression model (using estimates) and implements $\lambda=1/2$ fixed by feedback (thus typical PD feedback of desired trajectory) with a more aggressive reference feedforward $\lambda_{ff}=1$.

5. 3-PARAMETER REGRESSION

When the inertia cross-produces are relatively small, they may be neglected resulting in the following regression model.

$$\left[\Phi(\omega_r, \dot{\omega}_r)\right]_{3x3} \{\hat{\Theta}\}_{3x1} \begin{bmatrix} \dot{\omega}_x & -\omega_y\omega_z & \omega_z\omega_y \\ \omega_x\omega_z & \dot{\omega}_y & -\omega_z\omega_x \\ -\omega_x\omega_y & \omega_y\omega_x & \dot{\omega}_z \end{bmatrix}_r \begin{Bmatrix} \hat{J}_{xx} \\ \hat{J}_{yy} \\ \hat{J}_{zz} \end{Bmatrix}$$

Equation (26): Reduced-order 3-parameter feedforward

The second proposed adaptive technique (*Proposed3*) utilizes this regression model (replacing inertia with estimates), and implements $\lambda=1/2$ fixed by feedback (thus typical PD feedback of desired trajectory) with a more aggressive reference feedforward $\lambda_{ff}=1$.

6. SIMULATIONS

In this section, a nominal target acquisitions and tracking maneuver is performed with various control techniques to compare performance. The maneuver consists of a steady yaw (earth-tracking maneuver) and sinusoidal pitch (target evasion) with equations given below in

Fig 3. Older estimated values of the experimental testbed's inertia (prior to installation of the optical payload) are used to design the feedforward torque command. Since the actual new inertia is unknown, equation 27 assumed-actual inertia components were assumed to design the classical "perfect" feedforward control for comparison. Simulated spacecraft inertia $[J]_{actual\_simulated}$ was increased 10% arbitrarily from what was assumed in the design of the feedforward control $[J]_{feedforward}$.

Figures 5-11 display simulation results which reveal considerable performance-increase using Slotine/Fossen's adaptive control. A reduced-form 6-parameter adaptive control scheme proves to perform identically well. Furthermore, eliminating reference trajectory feedback replacing it with simple PD feedback allows more aggressive adapted feedforward improving performance slightly further compared to Slotine-Fossen's method. Selection of feedforward reference trajectory gain λ_{ff} establishes the limits of performance increase. Higher λ result in better performance. Note that assuming a diagonal inertia matrix (using the 3-parameter adaptive control) is superior to classical feedforward plus PD feedback control, but does not perform as well as the higher computational adaptive controls for this assumed spacecraft with non-negligible inertia off-diagonal terms (equation 27).

$$[\mathbf{J}]_{feedforward} = \begin{bmatrix} 119.1259 & -15.7678 & -6.5486 \\ -15.7678 & 150.6615 & 22.3164 \\ -6.5486 & 22.3164 & 106.0288 \end{bmatrix} \tag{27}$$

$$10 < t < 18 : \begin{Bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ -8\left(\dfrac{\pi}{16}\right)^2 \sin\left(\dfrac{\pi}{16}(t-10)\right) \end{Bmatrix} \qquad 18 < t < 20 : \begin{Bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ -15\left(\dfrac{\pi}{16}\right)^2 \sin\left(\dfrac{\pi}{16}(t-10)\right) \end{Bmatrix}$$

$$t > 20 : \begin{Bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{Bmatrix} = \begin{Bmatrix} -\left(\dfrac{2\pi}{30}\right)^2 \cos\left(\dfrac{2\pi}{30}t\right) \\ 0 \\ -\left(\dfrac{1}{10}\right)^2 \left(\dfrac{2\pi}{10}e^{-t} - te^{-t}\right) \end{Bmatrix}$$

Fig 3 Commanded target acquisitions (10<t<20) and tracking trajectory (t>20) for evaluation in simulations and experimental verification.

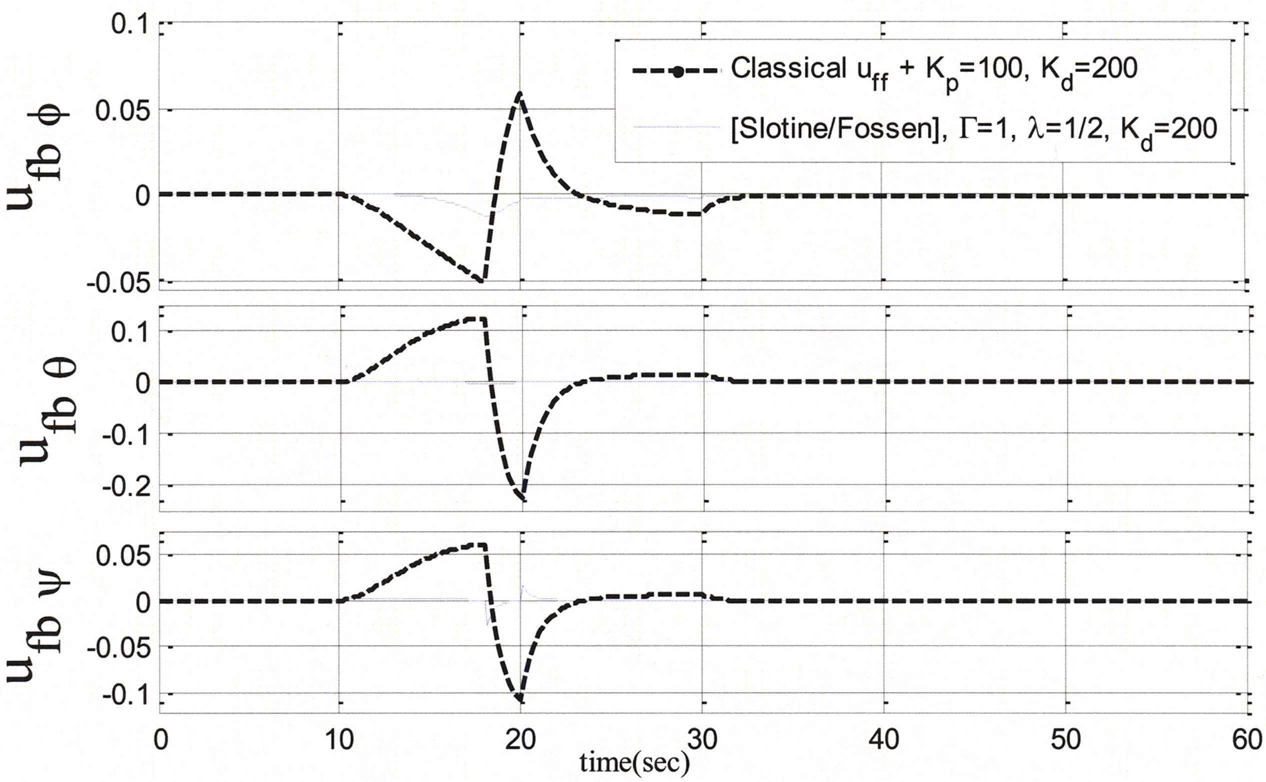


Fig 4. FEEDBACK CONTROLS: Classical feedforward + PD feedback Versus Slotine/Fossen adaptive control

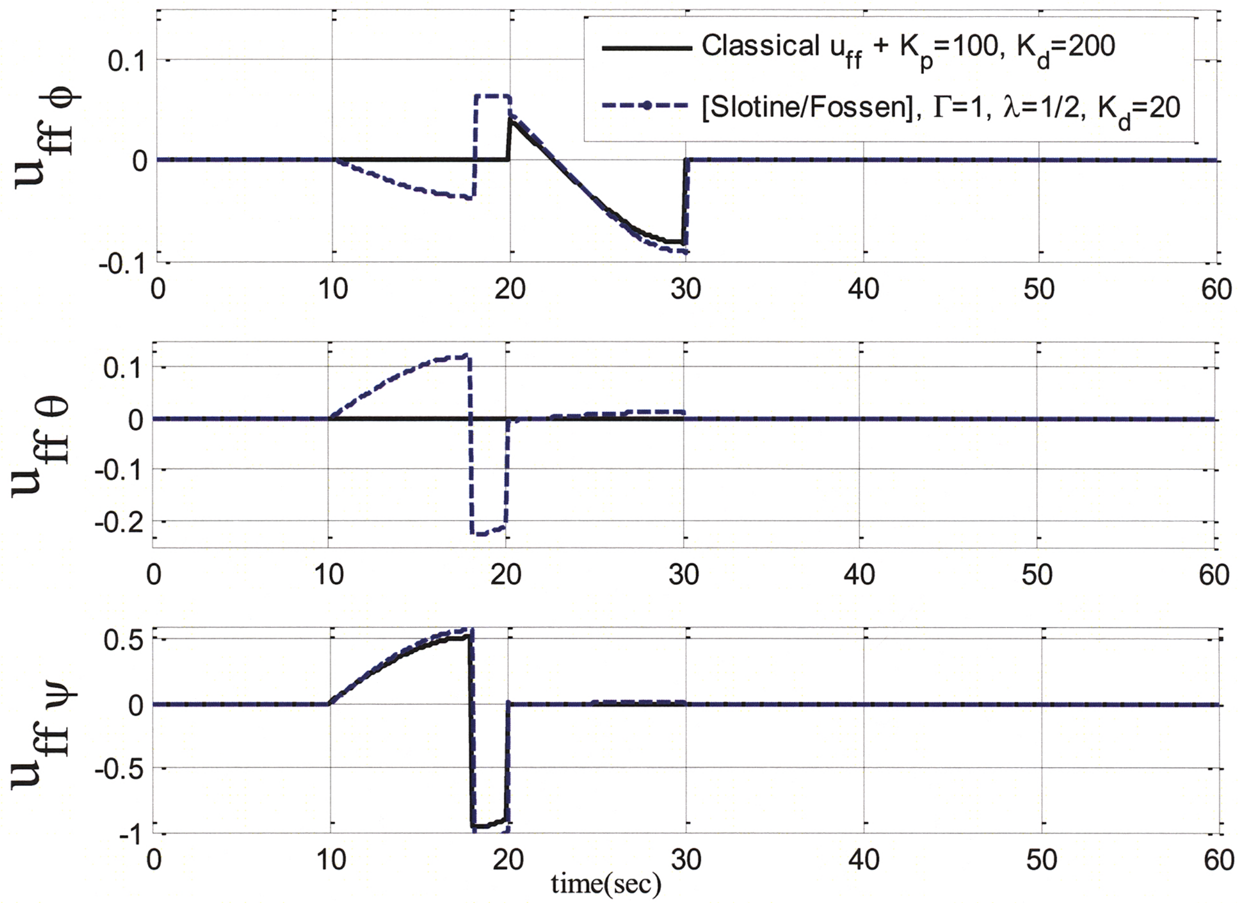


Fig 5 FEEDFORWARD CONTROLS: Classical feedforward + PD feedback Versus Slotine/Fossen adaptive control

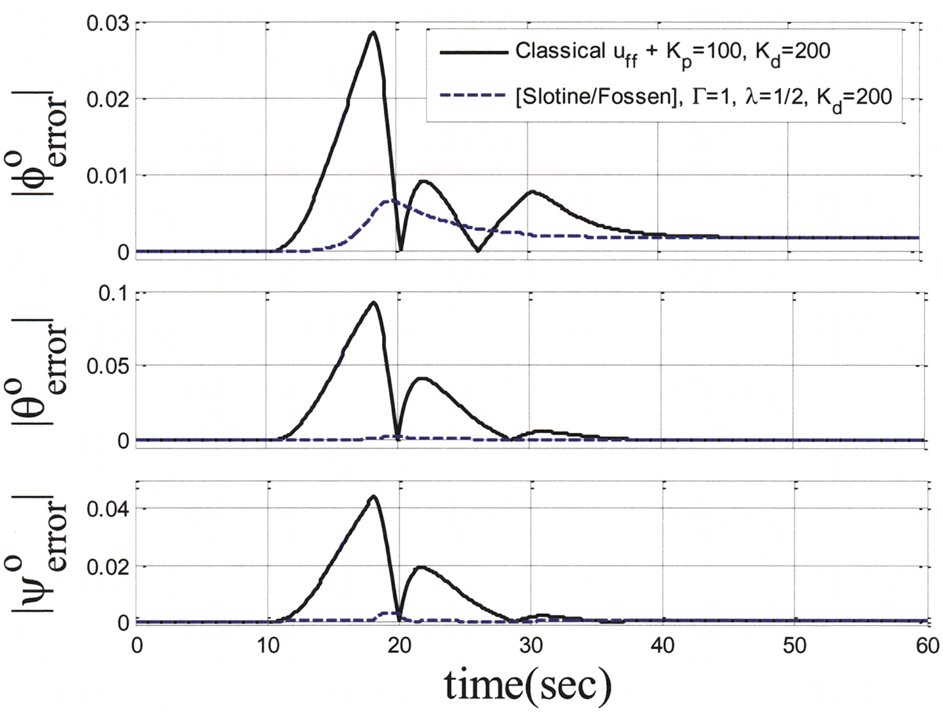


Fig 6 TRACKING ERRORS: Classical feedforward + PD feedback Versus Slotine/Fossen adaptive control

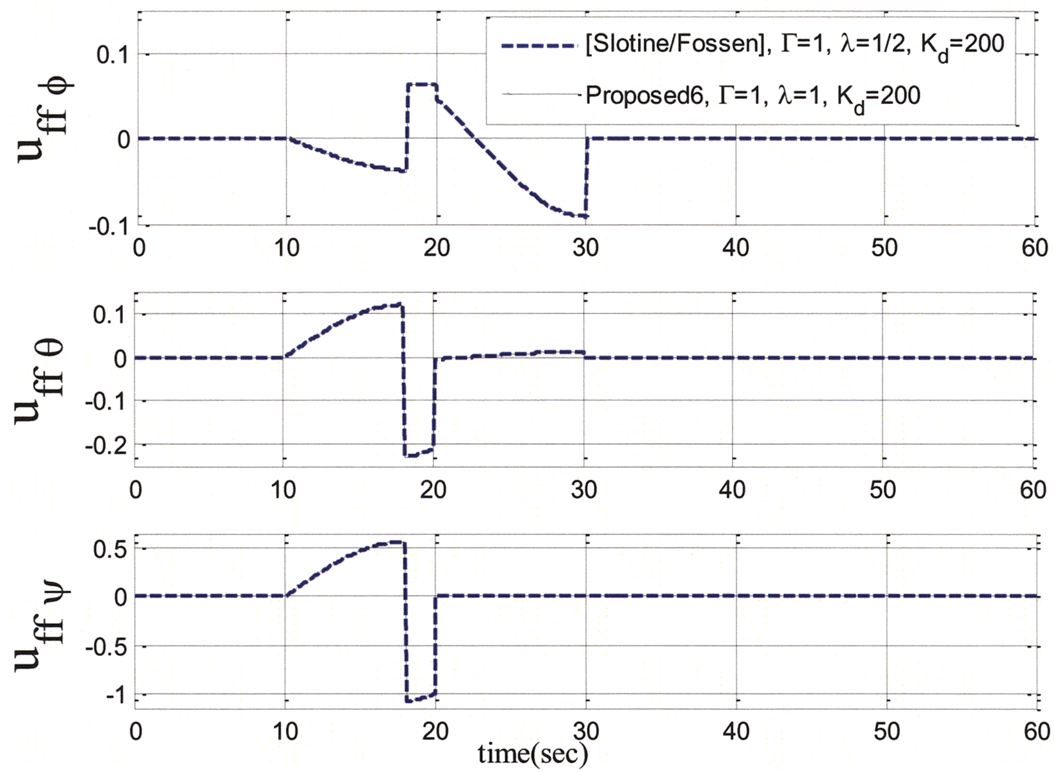


Fig 7 FEEDFORWARD CONTROLS: Slotine/Fossen Vs. *Proposed6* adaptive feedforward (only) with PD feedback control

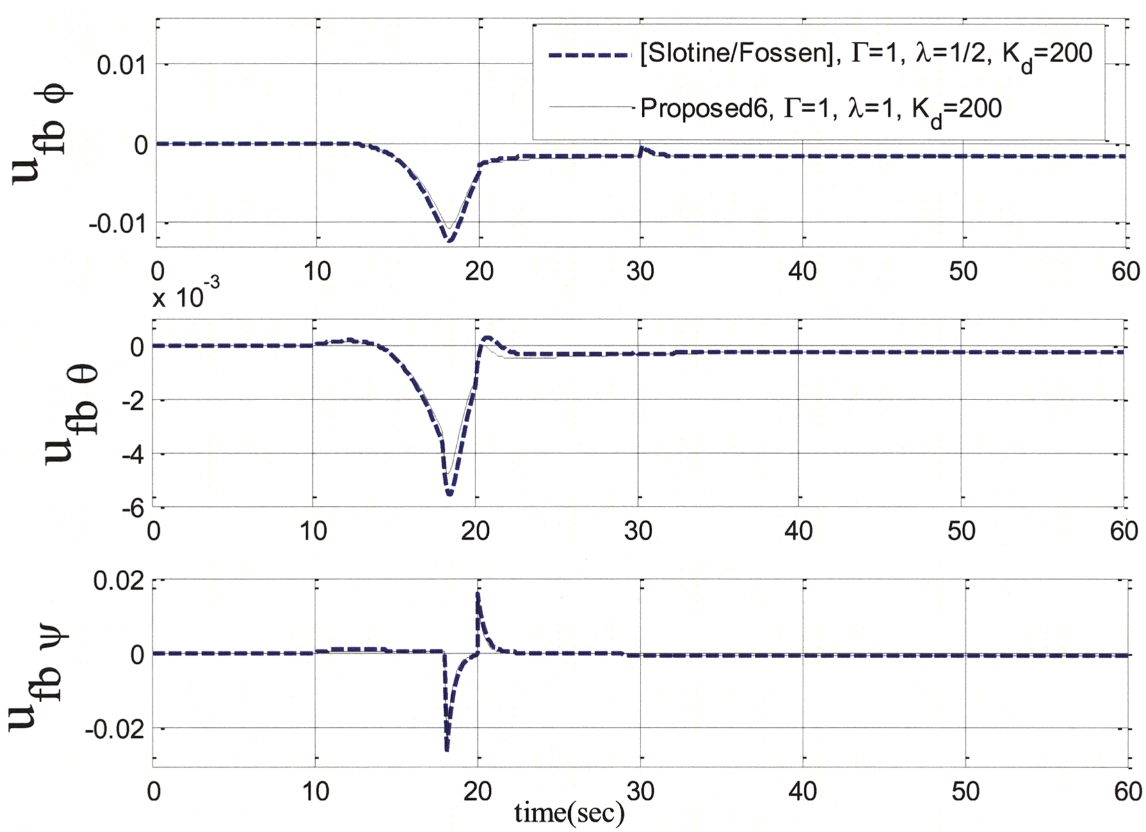


Fig 8 FEEDBACK CONTROLS: Slotine/Fossen Vs. *Proposed6* adaptive feedforward (only) with PD feedback control

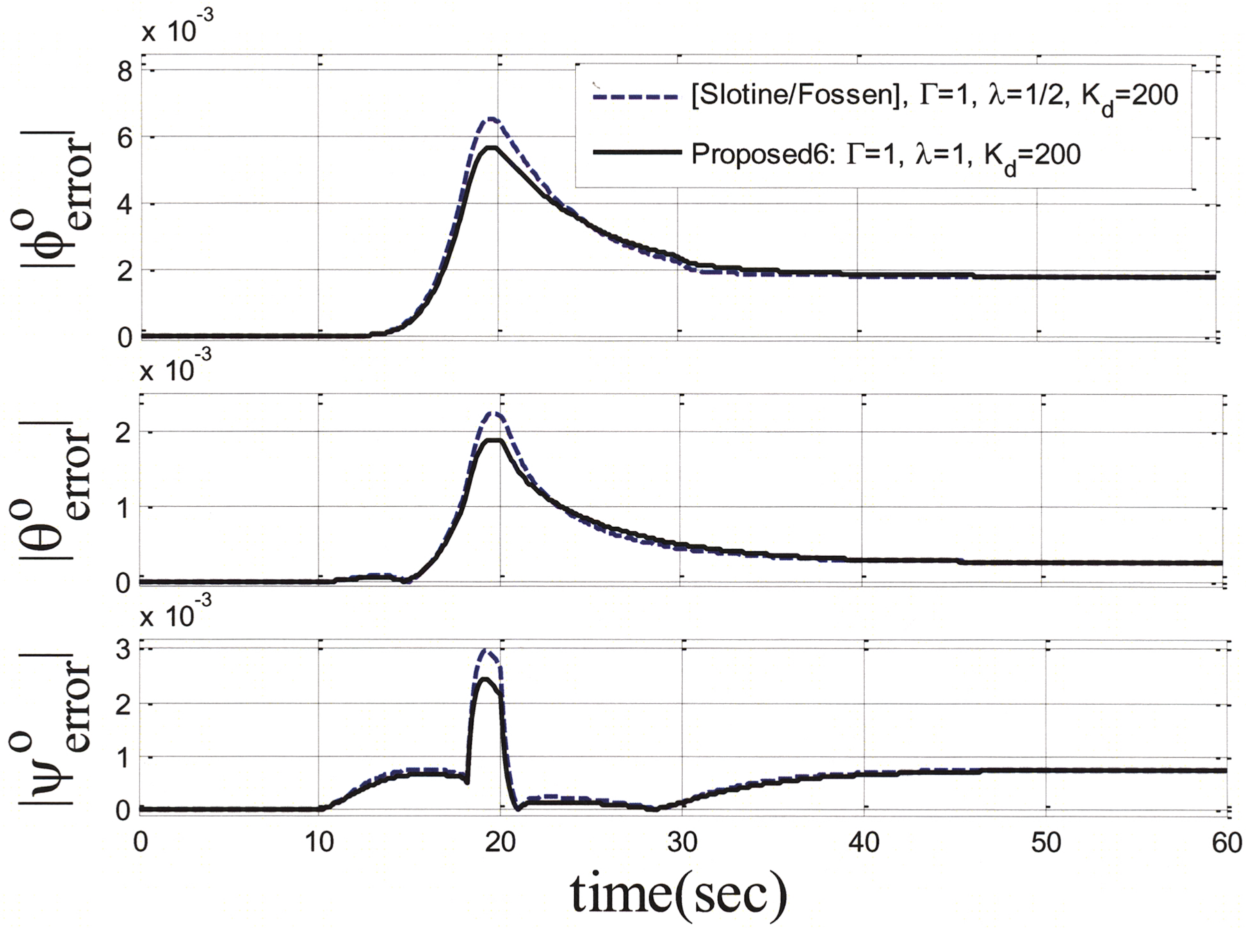


Fig 9 TRACKING ERRORS: Slotine/Fossen Vs. *Proposed6* adaptive feedforward (only) with PD feedback control

60 Sec. ATP simulation, $[\mathbf{J}]_{error}$=10%	RMS error ϕ^o	RMS error θ^o	RMS error ψ^o
Kp=100, Kd=200 (feedback only)	1.16e-2	1.13e-2	4.69e-2
Classical u_{ff} + Kp=Kd=200 **BASELINE**	4.18e-3	1.03e-2	4.97e-3
[Slotine/Fossen] λ=1/2, Γ=1, K_d=200	1.84e-3	3.87e-3	5.21e-4
Derived-6 λ=1/2, Γ=1, K_d=200	1.84e-3	3.87e-3	5.21e-4
Proposed-6: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	1.81e-3	3.80e-4	4.75e-4
Proposed-3: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	2.54e-3	6.27e-3	5.00e-4

Table 1 No-noise simulation RMS error summary

Due to the high pointing accuracy achieved, the RMS errors are correspondingly small. Accordingly, a percent-improvement summary is quite revealing. Classical feedforward plus feedback control was established as the baseline, and the feedback gains were normalized for all cases. The 9-parameter approach inspired by Slotine/Fossen provided significant performance increase. Additionally, the derived, reduced-order 6-parameter regression provided equivalent performance (as anticipated). The proposed 6-parameter regression (with decoupled, more aggressive adaptive feedforward) slightly improved performance still further, while the proposed 3-parameter regression adaptive controller provided significantly improved performance with a simple controller.

60-sec. ATP simulation, 10% Inertia error: ***Percent Performance increase***			
Control Method (*baseline)	$-\%\ \phi^o$	$-\%\ \theta^o$	$-\%\ \psi^o$
[Classical u_{ff} + Kp=Kd=200]*	0.00 %	0.00 %	0.00 %
[Slotine/Fossen] λ=1/2, Γ=1, K_d=200	56.06%	96.25%	89.52%
Derived-6 λ=1/2, Γ=1, K_d=200	56.06%	96.25%	89.52%
Proposed-6: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	56.86%	96.32%	90.45%
Proposed-3: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	39.42%	39.18%	89.94%

Table 2 Simulation comparison: % performance increase

7. EXPERIMENTAL VERIFICATION

While many modern algorithms seem promising on paper, real world situations often confound many such algorithms. With this motivation, the proposed new control algorithms presented here have been experimentally verified on a free-floating, three-axis spacecraft simulator. Spacecraft actual inertia (6) components are unknown. Previous values (prior to payload installation) listed above (Figure 3) are used for classical control design and initializing adaptive controllers.

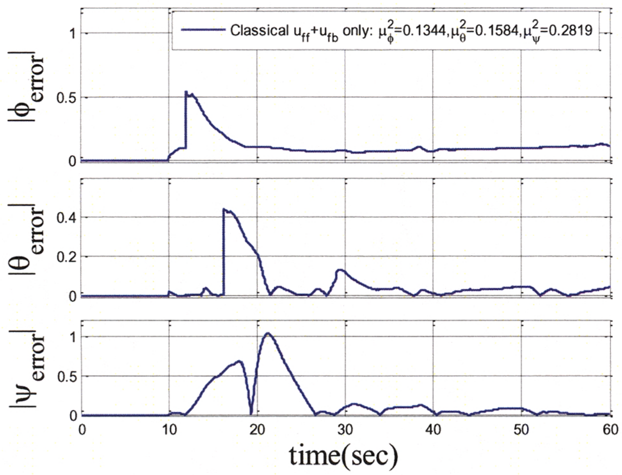


Fig 10 EXPERIMENT for large-angle acquisition maneuver followed by target tracking trajectory.

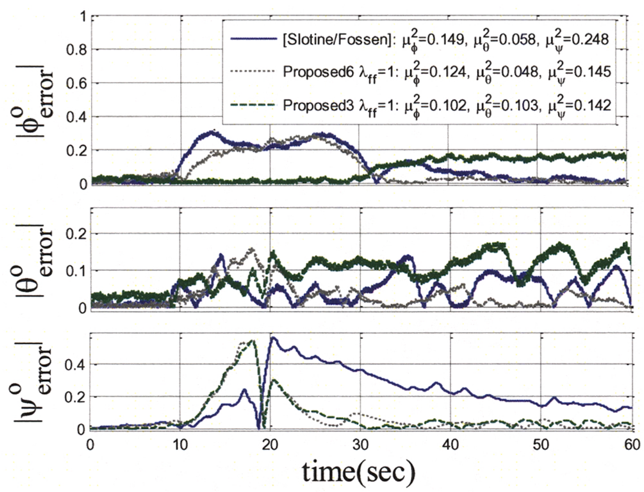


Fig 11 EXPERIMENT for large-angle acquisition maneuver followed by target tracking trajectory.

60-sec. ATP **experiment**: Percent Performance increase			
Control Method (*baseline)	$-\%\ \phi^o$	$-\%\ \theta^o$	$-\%\ \psi^o$
[Classical u_{ff} + Kp=Kd=200]*	0.00 %	0.00 %	0.00 %
[Slotine/Fossen] λ=1/2, Γ=1, K_d=200	10.9 %	74.7 %	25.2%
Proposed-6: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	7.7 %	114.3%	101.9%
Proposed-3: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	24.1 %	41.2 %	104.1%

Table 3 EXPERIMENT RMS ERROR SUMMARY for large-angle acquisition maneuver followed by target tracking trajectory.

Figures 12 displays experimental tracking errors (roll ϕ, pitch θ, yaw ψ in degrees) for the baseline Classical feedforward + PD feedback control with Kp=100, K_d=200. Figure 13 displays a experimental tracking errors (roll ϕ, pitch θ, yaw ψ in degrees) comparison: [Slotine/Fossen] where λ=1/2, K_d=200; *Proposed6* adaptive feedforward & PD feedback control where where λ_{ff}=1, K_p=100, and K_d=200; *Proposed3* adaptive feedforward & PD feedback control where λ_{ff}=1, K_p=100, K_d=200.

Table 3 contains a summary of experimental performance increase in tracking errors (roll ϕ, pitch θ, yaw ψ in degrees) where u_{ff}=feedforward control, u_{fb}=feedforward control, K_p=proportional feedback gain, K_d=derivative feedback gain, [Slotine/Fossen] refers to method in respective literature, *Proposed6* refers to proposed 6-parameter adaptive feedforward, *Proposed3* refers to proposed 3-parameter adaptive feedforward.

Number of *additional* mathematical operations		
Control Method (*baseline)	Add & Multiply	Integrate
[Classical u_{ff} + Kp=Kd=200]*	--	--
[Slotine/Fossen] λ=1/2, Γ=1, K_d=200	68	1
Proposed-6: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	44	1
Proposed-3: λ_{ff}=1, Γ=1, K_d=200, λ_{fb}=½	8	1

Table 4 Algorithmic complexity comparison.

Having demonstrated performance increases, it is logical to examine the algorithmic cost of the enhancements. The number of mathematical operations (e.g. addition, multiplication) necessary to implement each control technique were counted and tabulated in table 4. Notice that the method inspired by Slotine/Fossen requires relatively more computations despite the proposed methods providing superior performance increase. Also consider the baseline control strategy included PD control (not PID control). If PID control were implemented that would also incur the penalty of an additional integrator.

8. CONCLUSIONS

This paper demonstrates enhanced spacecraft target acquisitions maneuvers and tracking performance utilizing simplified, stable, and convergent adaptive techniques for unknown inertia errors. Initially, a suggested method from the literature is derived and simulated with experimental verification on a free-floating spacecraft simulator. Next, two simplifications to the method in the literature are proposed and compared to the nominal method. The simplifications bestow algorithmic reduction while maintaining performance improvement over typical control methods. Lastly, an alternative adaptive control algorithm is introduced further improving performance and eliminating the reference-adaptation of the feedback signal. 39-96% performance increase is achieved in ideal simulations, and 7-104% improvement was validated experimentally as compared to classical feedforward plus PD feedback control noting the actual error in inertia estimates is unknown, since the experiments were performed on a large free-floating spacecraft simulator with unknown inertia (prior to exhaustive system identification).

Thus without knowing the spacecraft's actual on-orbit inertia, these algorithms may be used as plug-and-play replacements potentially eliminating the need for lengthy system identification. Certainly immediate aggressive maneuvering is possible if mission requirements dictate. Implementation is quite simple. Simply replace the feedforward inertia with an adapted inertia based on the simple adaption rule (equation 17) and the prerequisite reference trajectory (equations 4-5) which is also input to a typical PD controller. This paper demonstrated that using the desired trajectory for the feedback controller can provide a superior solution with an aggressive adaptive feedforward control based upon the reference trajectory.

Special thanks to Lieutenant Colonel Michael Pandolfo for his editorial efforts on this paper.

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Distinguished Professor Brij N. Agrawal is the Director of the Spacecraft Research and Design Center at the Naval Postgraduate School, Monterey California. He worked for twenty years for Communications Satellite Corporation (COMSAT) and International Telecommunications Satellite Organization where he conducted research in spacecraft attitude control, spacecraft structures, spacecraft system designs, and spacecraft testing. He participated in the development of INTELSAT IV, IV-A, V, VI, COMSTAR and MARISAT satellites. He wrote the first text book on spacecraft design "Design of Geosynchronous Spacecraft" and was awarded a patent on attitude pointing error correction system for geosynchronous spacecraft.