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# Orbital mechanics and formation flying

## A digital control perspective

Pedro A. Capó-Lugo and Peter M. Bainum

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## A digital control approach

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AND

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To my wife, my newborn son, and my family, thanks for their patience and support.

*Pedro A. Capó-Lugo*

To my wife, my son, and his wife for their support and understanding.

*Peter M. Bainum*

# List of symbols

| | |
|---|---|
| $\mathbf{A}$ | State matrix |
| $\hat{\mathbf{A}}$ | Discrete state matrix |
| $\mathbf{A}_{CL}$ | Closed loop matrix |
| $\mathrm{A}$ | Area of the ellipse |
| $\mathrm{A_F}$ | Axial force |
| $\mathrm{A_{VO}}$ | Area of the valve opening |
| ARE | Adjoint Riccati equation |
| $\vec{a}$ | Acceleration of the body |
| $\vec{a}_{0/1}$ | Acceleration of the body seen from the reference point |
| $\vec{a}_{2/0}$ | Acceleration of the body seen from the observer 2 near point O |
| $a$ | Semimajor axis |
| $a_t$ | Semimajor axis for the transfer orbit |
| $a_N$ | Coefficient of the polynomial |
| $\mathrm{a}$ | Semi-conjugate axis for the hyperbola |
| $\bar{\alpha}$ | Angle of attack |
| $\alpha$ | Angle of the incident light |

| | |
|---|---|
| $\boldsymbol{B}$ | Control matrix |
| $\hat{\boldsymbol{B}}$ | Discrete control matrix |
| $B_2$ | Constant describing the Earth oblateness |
| $B_C$ | Ballistic coefficient |
| $\bar{B}$ | Unit vector applied along the tangential direction |
| $B_0$ | Earth's magnetic field intensity |
| $\vec{B}_m$ | Earth's magnetic field vector |
| $\vec{B}_h$ | Horizontal component of the Earth's magnetic field vector |
| $b$ | Semiminor axis |
| $\hat{b}_i$ | Body coordinates |
| $\beta$ | Gimbal angle of the motors about the Y axis |
| $\beta_{max}$ | Maximum gimbal angle |

| | |
|---|---|
| $C$ | Controllability matrix |
| $\hat{C}$ | Discrete output matrix |
| $CG$ | Center of gravity |
| CM | Center of mass |
| $CP$ | Center of pressure |
| $c$ | Number of constraints |
| $c(t)$ | Surface constraint |
| $C_D$ | Drag coefficient |
| $\bar{c}$ | Velocity of light in vacuum |

| | |
|---|---|
| DOF | Degrees of freedom |
| $D$ | Magnetic declination |
| $D_E$ | Earth's magnetic dipole moment |
| $\vec{D}$ | Magnetic dipole moment |
| $D_{max}$ | Maximum magnetic dipole moment |
| $d$ | Distance from the center of the Earth to the directrix line |
| $d_{RW}$ | Damping of the reaction wheel |
| $\vec{d}$ | distance between parallel coordinate systems |
| $d(\ )$ | Change or variation of a variable |
| $\delta$ | Gimbal angle for the motors about the $Z$ axis |
| $\delta f$ | Difference in the true anomaly angle |
| $\Delta t$ | Change in time or sampling time |
| $\Delta f$ | Sampling time in the true anomaly angle |
| $\Delta V_{P,SB}$ | Change in velocity at the perigee point for SB |
| $\Delta V_{P,SA}$ | Change in velocity at the perigee point for SA |
| $\Delta V_{P,SC}$ | Change in velocity at the perigee point for SC |
| $\Delta V_{P,SH}$ | Change in velocity at the perigee point for SH |
| $\Delta V_a$ | Change in velocity at the apogee point |
| $\nabla f$ | Gradient of a function |

| | |
|---|---|
| $E(z)$ | Auxiliary variable in the discrete domain |
| $E$ | Eccentric anomaly |
| ECI | Earth centered inertial frame |
| $E_0$ | Light energy arriving at the infinitesimal surface |
| $E_b$ | Voltage across the rotor |
| $E_a(t)$ | Applied voltage |
| $E_{max}$ | Maximum applied voltage |
| $E_r^2$ | Mean square error |
| $e$ | Eccentricity of the orbit |
| $\epsilon_a$ | Absorptivity coefficient |

| | |
|---|---|
| $\epsilon_d$ | Diffuse reflectance coefficient |
| $\varepsilon$ | Reflectivity coefficient |
| $\xi,\zeta,\eta$ | Coordinate system of the center of mass |
| $e_x$ | Actual state error |
| $e_{\dot{x}}$ | Time derivative of the actual state error |

| | |
|---|---|
| $F$ | Final state weighting matrix |
| FS | First stage of Ares V |
| FL | Fuzzy logic |
| $F_A$ | Aerodynamic force |
| $\vec{F}$ | Forces applied to the body |
| $\bar{F}$ | Solar radiation force |
| $\vec{F}_i^b$ | Body forces |
| $\vec{F}_i^S$ | Surface forces |
| $\vec{F}^+$ | Solar radiation force for absorbing surface |
| $\vec{F}^-$ | Solar radiation force for reflective surface |
| $\vec{f}_{J2,M}$ | J2 perturbation force for the maneuvering spacecraft |
| $\vec{f}_{J2,R}$ | J2 perturbation force for the reference spacecraft |
| $\vec{f}_{P,M}$ | Perturbation force for the maneuvering spacecraft |
| $\vec{f}_{P,R}$ | Perturbation force for the reference spacecraft |
| $f$ | True anomaly angle |
| $f_L$ | Final true anomaly angle |
| $f_0$ | Initial true anomaly angle |
| $f_M$ | Frequency of the magnetic natural response function |
| $f_v$ | Damper constant |

| | |
|---|---|
| $G_P(S)$ | Transfer function for the process or plant |
| $G_A(S)$ | Transfer function for the actuator |
| $G_C(S)$ | Transfer function for the controller |
| $G_S(S)$ | Transfer function for the sensors |
| $G_{OL}(S)$ | Open loop transfer function |
| $G_{CL}(S)$ | Closed loop transfer function |
| $G$ | Universal gravitational constant |
| GA | Genetic algorithms |
| GP | Gimbal point |
| $\vec{G}$ | Adjoint Riccati equation |
| $\vec{G}_\infty$ | Steady-state adjoint Riccati equation |
| $\vec{\hat{G}}_\infty$ | Discrete steady-state adjoint Riccati equation |
| $g$ | Gravitational acceleration for the Earth |
| $\gamma$ | Flight path angle |
| $\gamma_L$ | Learning parameter |

| | |
|---|---|
| $\vec{\gamma}$ | Error vector |
| $\vec{\gamma}_\infty$ | Steady-state error vector |

| | |
|---|---|
| $H$ | Density scale height |
| $H_m$ | Flux density in the rod |
| $\mathcal{H}$ | Hamiltonian equation |
| $\vec{H}$ | Angular momentum of the body |
| $\vec{H}_T$ | Total angular momentum |
| $\vec{H}_{RW}$ | Reaction wheel angular momentum |
| $h$ | Angular momentum per unit mass |
| $\bar{h}$ | Power of electromagnetic wave per unit surface |
| $\bar{h}_0$ | Solar radiation constant |

| | |
|---|---|
| $\mathbf{I}$ | Identity matrix |
| $\hat{I}$ | Inertia matrix |
| $I$ | Magnetic inclination angle |
| $I_{max}$ | Maximum applied current |
| $I_{ij}$ | Moments of inertia, $i$=1,2,3 and $j$=1,2,3 |
| $I_a$ | Armature current |
| $I_{SP}$ | Specific impulse for any motor |
| $I_S$ | Current source |
| $i$ | Inclination angle |
| $i_S$ | Inclination angle of the Sun with respect to the Earth |

| | |
|---|---|
| $J$ | Principal moments of inertia |
| $J_{RW}$ | Reaction wheel moment of inertia |
| $\mathcal{J}$ | Cost function or system performance |

| | |
|---|---|
| $\mathbf{K}_\infty$ | Steady-state control gain matrix |
| $\mathbf{K}$ | Control gain matrix |
| $\mathrm{K}$ | Momentum of light |
| $K_b$ | Back electromotive force constant |
| $K_t$ | Motor torque constant |
| $K_P$ | Proportional control gain |
| $K_I$ | Integral control gain |
| $K_D$ | Derivative control gain |
| $\widetilde{K}_P$ | Proportional adaptive control gain |
| $\widetilde{K}_d$ | Derivative adaptive control gain |
| $K$ | Spring constant |
| $\vec{K}^{\mathrm{P}}_\infty$ | Steady-state perturbation gain vector |
| $k$ | Sample taken in the discrete control process |

| | |
|---|---|
| $L$ | Lagrange equation or Lagrange function |
| $\mathcal{L}\{\ \}$ | Laplace transform |
| $\mathrm{L}$ | Number of runs in the hierarchical control scheme |
| $L_a$ | Armature inductance |
| $L_{CP}$ | Distance from the CG to the CP |
| $L_{GP}$ | Distance from the CG to the GP |
| $L_{SRB}$ | Distance from the CG to the center of the nozzle of the SRB |
| LQR | Linear quadratic regulator |
| LHS | Left hand side |
| $l$ | Angular momentum |
| $l_C$ | Length of the cylinder |
| $\vec{\lambda}$ | Co-state variable |
| $\lambda$ | Longitude |
| $\lambda_{ecliptic}$ | Mean longitude of the ecliptic plane |
| $\lambda_{sun}$ | Mean longitude of the Sun |
| $\mathcal{M}$ | End conditions in the cost function |
| $M$ | Mean anomaly angle |
| $\bar{M}$ | Total system mass |
| $M_b$ | Mass of the body |
| $M_E$ | Mass of the Earth |
| $M_{sun}$ | Mean anomaly of the Sun |
| $m$ | Mass of the body |
| $m_0$ | Initial mass |
| $m_i$ | Mass of a particle |
| $\dot{m}$ | Mass ratio at the exit nozzle of any motor |
| $\dot{m}_{max}$ | Maximum mass flow rate |
| $\mu$ | Earth gravitational constant which is equal to $GM_E$ |
| $N$ | Number of particles |
| $N_F$ | Normal force |
| $N_f$ | Last sample obtained in the control solution |
| $N_{STALL}$ | Stall torque |
| $\bar{N}$ | Unit vector applied along the normal to the orbital plane |
| $\vec{N}$ | Torques |
| $\vec{\mathcal{N}}$ | End constraints |
| $\vec{N}_A$ | Torque due to the atmospheric pressure |
| $\vec{N}_{AR}$ | Torque due to the satellite angular momentum |
| $\vec{N}_E$ | Gravity-gradient torques |
| $\vec{N}_m$ | Magnetic torques |

| | |
|---|---|
| $\vec{N}_P$ | Torque due to perturbing forces |
| $\vec{N}_{RW}$ | Reaction wheel torques |
| $\vec{N}_{SP}$ | Torque due to solar pressure |
| $\vec{N}_T$ | Torque due to the thrusters |
| $N_{max}$ | Maximum torque due to the reaction wheels |
| $n$ | Mean motion |
| NN | Neural network |
| $n_T$ | Number of thrusters for the RoCS |
| $n_t$ | Number of turns of the coil |
| $\hat{n}$ | Normal vector to the surface |
| $\upsilon$ | Angular velocity of the reaction wheels |
| $\upsilon\_$ | No load angular velocity |

| | |
|---|---|
| $\Omega$ | Anti-symmetric or skew-symmetric matrix |
| $\Omega_E$ | Earth angular velocity about the polar axis |
| $\Omega$ | Right ascension of the ascending node |
| $\omega$ | Argument of perigee |
| $\omega_n$ | Natural frequency |
| $\vec{\varpi}$ | Angular velocity of the satellite |
| $\vec{\varpi}_R$ | Reference angular velocity of the satellite |
| $\vec{\varpi}_n$ | Mean motion of the angular velocity of the satellite |

| | |
|---|---|
| $\mathbf{P}$ | $P_\infty$ Steady-state Riccati matrix |
| $\hat{\mathbf{P}}_\infty$ | Steady-state discrete Riccati matrix |
| $\%OS$ | Percent of overshoot |
| $p$ | Semi-latus rectum |
| $\phi$ | Latitude |
| $\varphi$ | Roll angle |
| $\varphi_m$ | Damping function for the magnetic dipole system |
| $\varphi_n$ | Natural response function for the magnetic dipole system |
| $\xi$ | Damping coefficient |
| $\psi$ | Yaw angle |
| $\vec{\psi}$ | Perturbation column vector |
| $\vec{\psi}_A$ | Perturbation column vector for atmospheric density force |
| $\vec{\psi}_{SP}$ | Perturbation column vector for solar pressure force |
| $\vec{\psi}_{Unknown}$ | Perturbation column vector for unknown forces |

| | |
|---|---|
| $\mathbf{Q}$ | State weighting matrix |
| $\tilde{\mathbf{Q}}$ | State weighting matrix in the true anomaly angle |
| $Q$ | Dynamic pressure |
| $Q_j$ | Generalized forces |

| | |
|---|---|
| $q$ | Quaternion, and term in the Legendre polynomial expansion of the Earth's potential function |
| $q_i$ | Generalized coordinates |
| $q_e$ | Error quaternion |
| $q_c$ | Commanding quaternion |

| | |
|---|---|
| $\mathbf{R}$ | Rotational matrix |
| $\boldsymbol{R}$ | Control weighting matrix |
| $\tilde{\boldsymbol{R}}$ | Control weighting matrix in the true anomaly angle |
| $\boldsymbol{R}_J$ | Direction cosines matrix for the principal moments of inertia |
| $\bar{R}$ | Unit vector applied along the radial direction |
| $R_A$ | Armature resistance |
| $R_E$ | Radius of the Earth |
| $R_C$ | Radius of the cylinder |
| $RoCS$ | Roll control system |
| RHS | Right hand side |
| RE | Riccati equation |
| $R$ or $\vec{R}$ | Radius that defines the distance from the center of the Earth to the satellite |
| $\hat{\vec{R}}$ | Unit vector associated with $\vec{R}$ |
| $\vec{R}_m$ | Distance from the center of mass of the satellite to a point in the body of the satellite |
| $\vec{R}_{CM}$ | Distance from the center of the Earth to the center of mass of the satellite |
| $r_a$ | Radius of apogee |
| $r_0$, $R_{SUN}$ | Mean distance of the Earth to the Sun |
| $r_p$ | Radius of perigee |
| $\vec{r}$ | Position of the maneuvering satellite |
| $\vec{r}_i$ | Position vector of the body |
| $\vec{r}_2$ | Distance from point O to the particle |
| $\vec{\rho}(t)$ | Separation distance between a pair of satellites |
| $\vec{\rho}_{Traj}(t)$ | Separation distance between a pair of satellites from the trajectory system |
| $\vec{\rho}_{NAV}(t)$ | Separation distance between a pair of satellites from the navigation system |
| $\rho_{Prop}$ | Density of the propellant |

| | |
|---|---|
| $S$ | Satellite surface area |
| $\bar{s}$ | Altitude of the orbit |
| SRB | Solid rocket booster motors |

| | |
|---|---|
| $sgn(\ )$ | Signum function |
| $\hat{\sigma}$ | Direction of the light flux |
| $\varsigma$ | Function in terms of the true anomaly angle |

| | |
|---|---|
| T | Period of the orbit |
| $T_t$ | Period of the transfer orbit |
| $T_{JC}$ | Time in Julian centuries |
| $T_{JD}$ | Time in Julian dates |
| $T_{J2\text{-}X}$ | Thrust force for the J2-X engines |
| $T_{RoCS}$ | Thrust force for the RoCS |
| $T_{RS\text{-}68b}$ | Thrust force for the RS-68b motors |
| $T_{SRB}$ | Thrust force for the SRB motors |
| $T_{max}$ or $T_m$ | Maximum thrust force |
| $T_K$ | Kinetic energy |
| $T_{\mathrm{P}}$ | Time of perigee passage |
| $T_r$ | Rise time |
| $T_s$ | Settling time |
| $T_p$ | Peak time |
| TPBVP | Two point boundary value problem |
| *tol* | Tolerance value |
| $\vec{\Gamma}(k)$ | Solar pressure force disturbance vector |
| $\theta$ | Pitch angle |
| $\theta_A$ | Momentum parameter |
| $\vartheta$ | End conditions co-state variables |

| | |
|---|---|
| $U$ | Potential energy |
| US | Upper stage flight for Ares V |
| $U_L$ | Magnetic potential function |
| $U_e(k)$ | Unit value for the error containing the orbital elements |
| $U_X(k)$ | Unit value for the state vector containing the orbital elements |
| $u^*(t)$ | Particular control function |
| $u_A(t)$ | Actuator control function |
| $u_m(t)$ | Maximum input acceleration |
| $\vec{u}(t)$ | Control vector function |
| $\vec{u}_A(t)$ | Atmospheric force per unit mass |
| $\vec{u}_C(t)$ | Control vector function containing adaptive and baseline controller |
| $\vec{u}_{SP}(t)$ | Solar pressure force per unit mass |
| $\vec{\bar{u}}(t)$ | Adaptive control function |
| $\upsilon_f$ | Relative angular velocity of the satellite |

| | |
|---|---|
| $V$ | Energy equation |
| $V_L$ | Lyapunov homogeneous function |
| $\mathbb{V}$ | Volume |
| $V_{Prop}$ | Velocity of the propellant |
| $V_{P,SB}$ | Velocity at the perigee point for SB |
| $V_{P,SA}$ | Velocity at the perigee point for SA |
| $V_{P,SC}$ | Velocity at the perigee point for SC |
| $V_{P,SH}$ | Velocity at the perigee point for SH |
| $V_A$ | Velocity at the apogee point |
| $\vec{V}$ | Velocity of center of mass or velocity vector |
| $\hat{V}$ | Unit vector of the velocity vector |
| $v$ | Velocity equation |
| $v_{ESC}$ | Escape velocity |
| $v_p$ | Velocity at the perigee point |
| $v_i$ | Velocity of a particle |
| | |
| $W$ | Work done on a system |
| $W_V$ | Weight of the vehicle |
| $w$ | Sum of the true anomaly angle and the argument of perigee |
| $\bar{w}$ | Light energy per volume |
| $\vec{w}$ | Angular velocity |
| | |
| $X_B$, $Y_B$, $Z_B$ | Body coordinate frame |
| $X_R$, $Y_R$, $Z_R$ | Reference coordinate frame |
| $X_N$, $Y_N$, $Z_N$ | Nominal separation distance for the satellites in the ECI frame |
| $X_S$, $Y_S$, $Z_S$ | Initial separation distance for the satellites in the ECI frame |
| $\vec{X}$ | State vector for the orbital elements |
| $\vec{X}_D$ | State vector for the desired orbital elements |
| $x_{EM}$, $y_{EM}$, $z_{EM}$ | Magnetic field lines |
| $x_C(s)$ | Transfer function for the command function |
| $x_A(s)$ | Transfer function for the actuator function |
| $\vec{x}$ or $x_i$ | State vector ($i = 1,2,3,\ldots$) |
| $\vec{x}_0$ | Initial condition |
| $\vec{x}_1$ | Final condition |
| $\vec{x}_D$ | Desired state vector |
| | |
| $\vec{y}$ | Linear transformation in the true anomaly angle of the separation distance |

| | |
|---|---|
| $Z\{\ \}$ | Z-transform |
| $\vec{z}$ | State variables with integral terms |
| $\int_{\mathbb{V}} (\ )\, d\mathbb{V}$ | Volumetric integral |

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*Peter M. Bainum*

# Preface

This preface attempts to summarize the objective of this text. The authors have more than 54 years of practical real-world experience and attempt to encompass this experience in the chapters and suggested problems. Many of these problems have been adapted from these actual space projects and cannot be found in many contemporary text books.

This book will be used by practicing engineers and other texts may provide a deeper theoretical background. The reader can refer to more than 170 historical references, beginning with Arthur C. Clarke's 1945 reference describing his ideas for formation flying of three communication stations in a geosynchronous orbit in order to provide, through relay technology, instantaneous communication to/from any location on the Earth's surface, and also to/from various orbiting spacecraft.

Although the text begins with a review of orbital mechanics, the emphasis here is placed on digital control techniques and specific application for formation flying, deployment, station keeping, and reconfiguration. Part of the formation flying is based on research contracts with the Applied Physics Laboratory, and DARPA, focusing on on-track (string of pearls) and 3-D tetrahedron configurations in highly elliptical orbits. The tetrahedron was suggested as part of a design challenged by NASA Goddard.

Advanced modern control techniques, including intelligent control applications such as fuzzy logic, hierarchical control, and adaptive control, are proposed for the first time for formation flying applications. Some of these methods have been previously implemented for industrial applications, such as in the use of stepper motors.

Where possible, problems with analytical or closed-form solutions are suggested; in some cases a background in MATLAB and ability to solve nonlinear differential equations and in discrete form is assumed, as well as the ability to produce results in graphical format. In some cases answers and/or hints are provided. The philosophy here is that most of us learn by practicing, which means by working problems of various degrees of difficulty. Suggested problems attempt to follow the material covered in the preceding chapter.