UNIVERSITI PUTRA MALAYSIA

SPACECRAFT FORMATION FLYING RESPONSIVE MISSION OPTIMUM DELTA-V AND GROUND PERFORMANCE MEASURES

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By

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Chair : Prof. Dato' Dr.-Ing. Ir. Renuganth Varatharajoo, PhD
Faculty : Engineering

The slow turnaround time issue dwindling with a new planned space mission which is to cater for a rapid Earth's surface observation demand had stimulated the growing interest in the concept of responsive space mission. Weighing on all the factors that involved, initiating a brand new dedicated single spacecraft mission proved to be rather time-consuming and not cost-effective, especially when the acquisition of an instantaneous critical land information is prioritized for. Therefore, the best solution to this problem is to slew the existing distributed space platform to the desired land area of interest. In this research, a case study was conducted by manipulating the satellite formations that are operating in orbit to fulfill the demands for the responsive space. The selection of the spacecraft formation flying mechanism meant to address the stated problem was due to its better performances delivered, simple structures, high reliability and longer operating lifetime compared to any other approaches available in the field. Both findings on the orbit and ground segment analyses derived from the formation flying application will be presented with the main objective is to acquire the optimum results for solving the problems. Particularly for an orbital analysis subject, each stage of the flight to be examined along with its corresponding configuration until the formation established on the final responsive orbit to determine the right amount of fuel needed. This case study employed three different modes of finite-thrust impulse namely, the one-impulse transfer, the two-impulse transfer, and the three-impulse transfer maneuver to find the required local minimum and the global minimum delta-V during the formation orbital transfer phase. As for the ground segment analysis, formation performances were measured based on four implicit variables, namely the formation ground area of coverage, the overlap coverage area, the formation ground swath length, and the formation relative

geodesic. Cross-studies of these inter-dependent parameters were conducted at varying formation distances, altitudes, as well as inclinations, to acquire some specific trends so as to determine the optimum configuration for the excellent formation ground metric performance.

Case study results revealed the practicality of employing satellite formation flying to address the needs for a responsive space mission both in terms of the orbital fuel preference and the ground metric requirement. The novel graphing techniques exploiting the plots of some dependent variables enables the decision to be made faster. Furthermore, the proposed technique has the advantage of providing multiple potential solutions instead of a single solution that is acquired through the conventional approach of solving the derived analytical approximated formulation. For an orbital transfer phase, the solutions to the problem of fuel optimization constituting different types of finite impulse transfers can be found from the selected graphs, which contain some distinct signature features. In the event where the leader-follower formation is established, the higher amount of consumed retrograde fuel is necessary to retain the longitudinal separation between them as the formation separates farther. Several other factors that contribute to this delta-V variation include the total transfer time until target site arrival, the operating initial orbit semi-major axis, and the number of orbit revolution made. While the formation reconfiguration stage is equally critical, the fuel amount needed is found to be directly proportional to the increment in the formation distances. In addition to these factors, the formation ground assessment revealed that by positioning the formation at the right altitude within the low Earth orbit region while orbiting the Earth at high polar orbit inclination angle at near distance formation will produce the criterion of optimal desired ground performance. The criterion is the large acquisition of land coverage area, which has longer and wider ground coverage swath while possessing the least possible relative geodesic anomaly. Further investigation found that the occurrence of geodesic lengthening and shortening phenomenon were mainly influenced by the factor of sub-satellite point at high latitude positioning and the right azimuthal angle. Consequently, the presence of inconsistent relative geodesic attributes has significantly altered the overall computation accuracies of the ground area of coverage and its swath length properties.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGUKURAN PRESTASI PERMUKAAN BUMI DAN PERUBAHAN HALAJU ΔV PALING MINIMUM BAGI MISI RESPONSIF SATELIT DALAM PENERBANGAN FORMASI

Oleh

NOR AFFENDY BIN YAHYA

Februari 2022

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Isu berkaitan dengan tempoh reaksi yang lambat yang mempengaruhi rancangan misi angkasa yang baru yakni untuk memenuhi keperluan spontan pencerapan permukaan bumi telah merangsang minat ke arah konsep misi angkasa responsif. Dengan mengambilkira semua faktor yang berkaitan, perancangan untuk merekabentuk misi kapal angkasa yang baru terbukti memakan masa yang panjang dan tidak efektif dari segi kos terutamanya apabila pemerolehan data spontan permukaan bumi yang kritikal amat diutamakan. Jadi, penyelesaian terbaik kepada permasalahan ini adalah dengan melencong sekumpulan platform angkasa yang sedia ada ini supaya ia terbang melalui kawasan permukaan Bumi yang dikehendaki. Di dalam penyelidikan ini, satu kajian kes telah dijalankan dengan memanipulasikan formasi satelit yang sedang beroperasi di orbit untuk memenuhi objektif-objektif misi responsif angkasa. Pemilihan mekanisma penerbangan formasi satelit yang bertujuan untuk menyelesaikan masalah kajian kes adalah disebabkan oleh faktor-faktor prestasi yang lebih baik, strukturnya yang ringkas, kebolehharapan yang tinggi, dan jangka hayat operasi yang panjang berbanding dengan kaedah-kaedah lain yang ada dalam bidang tersebut. Hasil kajian berkaitan analisis segmen orbit dan permukaan bumi yang diperolehi dari pengaplikasian penerbangan formasi akan dibentangkan dengan objektif utama untuk memperolehi keputusan optimum bagi menyelesaikan masalah-masalah tersebut. Bagi subjek analisis orbit, setiap fasa penerbangan dengan konfigurasi tertentu yang terbang sehingga formasi itu mengorbit Bumi di orbit akhir responsif akan dianalisa secara spesifik untuk menentukan sukatan yang betul bagi bahan bakar yang diperlukan. Kajian kes ini menganalisa 3 jenis mod impuls tujah terhingga iaitu

kemudi impuls tunggal, kemudi 2-impuls dan kemudi 3-impuls untuk mencari nilai delta-V minimum lokal dan global yang diperlukan semasa fasa pindahan orbit formasi. Untuk analisis segmen Bumi, prestasi formasi diukur berdasarkan kepada 4 pembolehubah tersirat iaitu liputan luas tanah formasi, luas liputan tertindih, kepanjangan petak tanah formasi, dan geodesik relatif formasi. Kajian bersilang semua parameter-parameter yang tersangkut-paut ini pada jarak formasi, ketinggian altitud dan kecondongan orbit yang berbeza-beza dijalankan untuk mendapatkan corak spesifik yang akan membawa kepada konfigurasi optimum untuk prestasi ukuran terbaik bagi formasi di permukaan Bumi.

Keputusan kajian kes menunjukkan kesesuaian penggunaan aplikasi penerbangan formasi satelit bagi memenuhi kehendak misi angkasa responsif dari segi keperluan jumlah bahan bakar di orbit dan ukuran permukaan Bumi yang diperlukan. Teknik baru yang dicadangkan ini yang mengeksploitasi plot-plot graf yang terdiri daripada pembolehubah-pembolehubah bersandar telah membolehkan keputusan dibuat dengan lebih pantas. Selain itu, teknik alternatif yang diperkenalkan mempunyai kelebihan untuk memberikan potensi penyelesaian pelbagai berbanding hanya satu penyelesaian sahaja yang diperolehi melalui kaedah konvensional iaitu penyelesaian formula teranggar analitikal yang diterbitkan. Bagi fasa pindahan orbit, penyelesaian kepada masalah pengoptimuman bahan bakar yang merangkumi pelbagai jenis kes impuls terhingga boleh diperolehi dari graf-graf terpilih yang mempunyai ciri-ciri spesifik graf yang unik. Dalam situasi di mana formasi ketua-pengikut telah dibentuk, dengan pertambahan jarak formasi, jumlah bahan bakar untuk tujahan songsang yang diperlukan adalah lebih tinggi bagi mengekalkan penjarakkan longitudinal antara mereka. Faktor-faktor lain yang menyumbang kepada variasi delta-V ini termasuklah jumlah masa untuk pindahan sehingga ketibaan di tapak Bumi yang disasarkan, paksi semi-major untuk orbit awal yang beroperasi dan bilangan kitaran orbit yang dibuat. Sedang peringkat rekonfigurasi formasi juga tidak kurang pentingnya, jumlah bahan bakar yang diperlukan didapati berkadar terus dengan peningkatan jarak formasi. Tambahan pula, penilaian permukaan Bumi formasi mendapati bahawa dengan meletakkan formasi pada ketinggian dalam lingkungan orbit rendah Bumi sambil mengelilingi Bumi pada sudut kecondongan orbit polar tinggi pada jarak formasi yang dekat akan membolehkan kita mencapai kriteria-kriteria prestasi permukaan Bumi optimum yang diingini. Kriteria ini adalah kawasan liputan tanah yang besar yang mempunyai petak liputan tanah yang lebar dan panjang di samping memiliki anomali geodesik relatif seminimum mungkin. Penyiasatan lanjut mendapati pembentukan fenomena kependekkan dan kepanjangan geodesik adalah dikonfigurasikan oleh faktor kedudukan titik sub-satelit pada latitud tinggi dan sudut azimuthal yang betul. Kesannya, kehadiran ciri-ciri tidak sekata ini telah mengubah seluruh ketepatan pengiraan kawasan permukaan Bumi yang diliputi dan sifat-sifat kepanjangan petak permukaan Bumi.

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Thank you.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AOC	Area of Coverage
BVP	Boundary Value Problem
CBR	Case-Based Reasoning
COV	Calculus of Variation
CSI	Constant Specific Impulse
DLQR	Direct Linear Quadratic Regulator
DoD	Department of Defence
ECEF	Earth-Centered Earth Fixed
ECI	Earth-Centered Inertial
FF	Formation Flying
GAST	Greenwich Apparent Sidereal Time
GCO	General Circular Orbit
GMST	Greenwich Mean Sidereal Time
GPS	Global Positioning System
GSFC	Goddard Space Flight Centre
HCW	Hill-Clohessy-Wiltshire
IAA	Instantaneous Access Area
INT	Integer Number
IOCA	Instantaneous Overlap Coverage Area
JD	Julian Day

LAST	Local Apparent Sidereal Time
LEO	Low Earth Orbit
LMST	Local Mean Sidereal Time
LPE	Lagrange Planetary Equation
LTH	Lawden-Tschauner-Hempel
LVLH	Local Vertical Local Horizontal
MST	Mean Sidereal Time
NASA	National Aeronautic and Space Administration
NGO	Non-Governmental Organization
OCA	Overlap Coverage Area
ORS	Operationally Responsive Space
PCO	Projected Circular Orbit
PWM	Pulse-Width Modulation
RAAN	Right Ascension of Ascending Node
SMC	Sliding Mode Control
STM	State Transition Matrix
TPBVP	Two-Point Boundary Value Problem
USAF	United State Air Force
UT	Universal Time
UTC	Universal Time Coordinate
UTM	Universal Transverse Mercator
WGS-84	World Geodetic System 1984

WMM	World Magnetic Model

LIST OF SYMBOLS

$\mathbf{O}$	Earth's center of mass or origin
Υ	Vernal equinox (First Point of Aries) direction
$\mathbf{O}_s$	Spacecraft center of mass
$\boldsymbol{r}_c$	Chief satellite orbit radius vector
r_c	Chief satellite mean orbit radius
a	Semi-major axis of satellite orbit
e	Eccentricity of satellite orbit
i	Inclination of satellite orbit
Ω	Right ascension of ascending node for satellite orbit
ω	Argument of perigee for satellite position in orbit
ν, θ, f	True anomaly for satellite position in orbit
M	Mean anomaly for satellite position in orbit
E	Eccentric anomaly
$O(q^i)$	q variable of the order of ith (i is integer number, $i =$ 0,1,2,3 ...)
$\hat{\mathrm{h}}$	Angular momentum vector
h	Orbit angular momentum scalar magnitude
$\hat{\mathrm{V}}$	Spacecraft velocity vector
ρ	Spacecraft relative motion distance in LVLH frame
S_c	Chief (leader) satellite
S_d	Deputy (follower) satellite

$\ddot{\boldsymbol{\rho}}_{\boldsymbol{R}}$	Spacecraft relative acceleration in co-rotating reference frame
$\ddot{\boldsymbol{\rho}}_{\boldsymbol{I}}$	Spacecraft observed acceleration in inertial frame
ω_a	Spacecraft angular velocity
$\dot{\omega}_a$	Spacecraft angular acceleration
$\dot{\boldsymbol{\rho}}_{\boldsymbol{R}}$	Spacecraft relative velocity in co-rotating reference frame
$\boldsymbol{\rho}_{\boldsymbol{R}}$	Spacecraft relative position in co-rotating reference frame
$\ddot{\boldsymbol{\rho}}_{\boldsymbol{x}}$	Satellite relative motion acceleration vector in radial-track direction
$\ddot{\boldsymbol{\rho}}_{\boldsymbol{y}}$	Satellite relative motion acceleration vector in along-track direction
$\ddot{\boldsymbol{\rho}}_{\boldsymbol{z}}$	Satellite relative motion acceleration vector in cross-track direction
$\dot{\boldsymbol{\rho}}_{\boldsymbol{x}}$	Satellite relative motion velocity vector in radial-track LVLH frame
$\dot{\boldsymbol{\rho}}_{\boldsymbol{y}}$	Satellite relative motion velocity vector in along-track LVLH frame
$\dot{\boldsymbol{\rho}}_{\boldsymbol{z}}$	Satellite relative motion velocity vector in cross-track LVLH frame
$\boldsymbol{\rho}_{\boldsymbol{x}}$	Satellite relative motion position vector in radial-track LVLH frame
$\boldsymbol{\rho}_{\boldsymbol{y}}$	Satellite relative motion position vector in along-track LVLH frame
$\boldsymbol{\rho}_{\boldsymbol{z}}$	Satellite relative motion position vector in cross-track LVLH frame
$\dot{\rho}_x$	Satellite relative motion magnitude first derivative in radial-track direction

$\dot{\rho}_y$	Satellite relative motion magnitude first derivative in along-track direction
$\dot{\rho}_z$	Satellite relative motion magnitude first derivative in cross-track direction
n_0, n_c	Chief satellite mean motion
$\delta a, \Delta a$	Semi-major axis difference
$\delta e, \Delta e$	Eccentricity difference
$\delta i, \Delta i$	Inclination difference
$\delta \Omega, \Delta \Omega$	Right ascension of ascending node difference
$\delta \omega, \Delta \omega$	Argument of perigee difference
$\delta M, \Delta M$	Mean anomaly difference
$\delta \theta$	True anomaly difference
a_0, a_c	Chief satellite orbit semi-major axis
a_d	Deputy satellite orbit semi-major axis
a_i, a_f	Satellite initial and final orbit semi-major axis, respectively
a_r	Acceleration vector component in radial-track direction
a_θ	Acceleration vector component in along-track direction
a_h	Acceleration vector component in cross-track direction
M_0	Chief satellite mean anomaly
M_s	Mean anomaly of chosen site
M_{fi}	Satellite mean anomaly in final orbit where impulse firing occur
M_{fs}	Satellite mean anomaly of the chosen site in final orbit

N_R	Number of orbit revolution
t_0	Initial time
μ	Earth gravitational constant, GM = $3.986 \times 10^{14} m^3/s^2$
p	Semi-latus rectum
ε_c	Chief satellite orbital energy
ε_d	Deputy satellite orbital energy
T_c	Chief satellite orbital period
T_d	Deputy satellite orbital period
α_0	Satellite formation initial phase angle
f_{el}	Satellite true anomaly in elliptical orbit
J_0	Julian day
θ_{GMST}	Greenwich Mean Sidereal Time angle
θ_{GMST_0}	Greenwich Mean Sidereal Time angle at zero-hour Universal Time
φ_s	Geographical latitude coordinate for chosen site
λ_s	Geographical longitude coordinate for chosen site
α_{GMST}	GMST angle from vernal equinox (γ) direction to the initial sub-satellite point longitude coordinate
$\alpha_{GMST_{site}}$	GMST angle from vernal equinox (γ) direction to the site longitude coordinate
t_G	Satellite total flight time in GMST angle variable
D	Integer number of days
ω_E	Earth's rotation rate, $7.2921158553 \times 10^{-5}$ rad/s

$\Delta\alpha$	Difference between $\alpha_{GMST_{site}}$ and α_{GMST} variable
$\Delta V_{min_{global}}$	Global minimum delta-V consumption
$\tilde{v}$	Spacecraft velocity vector
$\tilde{g}$	Gravitational acceleration function
Γ_{pv}	Thrust acceleration magnitude
$\hat{u}_T$	Thrust unit vector
T_{pv}	Thrust force magnitude applied in primer vector theory
m_s	Spacecraft mass
$\boldsymbol{x_0}$	Initial position vector
$\dot{\boldsymbol{x}}_{\boldsymbol{0}}$	Initial velocity vector
$\boldsymbol{x_f}$	Final position vector
$\dot{\boldsymbol{x}}_{\boldsymbol{f}}$	Final velocity vector
J_{pv}	Cost function parameter
ΔV	Velocity change (delta-V)
c_{ev}	Rocket effective exhaust velocity
m_0	Initial fuel mass
m_f	Final fuel mass
$\dot{m}_{pv}$	Mass flow rate
$\dot{m}_{pv\_max}$	Maximum mass flow rate
$\tilde{T}$	Maximum thrust
$\hat{u}$	Control variable
$\hat{u}_T^*$	Estimated optimum thrust direction vector

$\bar{p}_{pv}$	Primer vector variable
$\bar{\lambda}_{pv}, \bar{\mu}_{pv}, \bar{v}_{pv}$	Component of primer vector variable in Cartesian coordinate XYZ direction
$\hat{p}_{pv}$	Estimated primer vector value
p_{pv}	Primer vector magnitude
$\dot{p}_{pv}$	Primer vector magnitude first derivative
$\dot{\bar{p}}_{pv}$	Primer vector variable first derivative
$\ddot{\bar{p}}_{pv}$	Primer vector variable second derivative
G_r, G_v	Jacobian matrix
$\dot{G}_v$	First derivative of Jacobian matrix
G_v^T	Jacobian matrix transpose
$\Phi(t, t_0)$	State transition matrix from initial time, t_0 until time, t
$\Delta\bar{v}_{pv}$	Primer vector velocity change
$\Delta\hat{v}_{pv}$	Approximated change in velocity vector
$\Phi^{-1}(t_f, t_0)$	Inverse matrix of state transition matrix from final time, t_f to t_0
${\Delta V_{tot}}^2$	Square function of total delta-V consumption
ΔV_{tot}	Total delta-V consumed
ΔV_{min}	Minimum delta-V
S_{L1}	Ratio of Earth gravitational constant to orbit angular momentum in Lambert's solution
R_{L1}	Initial Keplerian orbit radius in Lambert's solution
R_{L2}	Final orbit radius in Lambert's solution

e_{L1}, e_{L2}	Initial and final orbit eccentricity in Lambert's solution, respectively
θ_{L1}, θ_{L2}	Satellite true anomaly in initial and final orbit in Lambert's solution
$\Delta V_{L1}, \Delta V_{L2}$	Initial and final orbit delta-V in Lambert's solution
ϕ_{L1}, ϕ_{L2}	Satellite flight path angle in initial and final orbit for Lambert's solution
P_{L1}, P_{L2}	Impulse firing points in initial and final orbit for Lambert's solution
q_{EL}	Generalized coordinate
$\dot{q}_{EL}$	Generalized velocity
$\tilde{Q}_{EL}$	Generalized constraint force
λ_{EL}	Lagrange multiplier
f_{EL}	Lagrange equation constraint function
s_m	Number of particle mass
M_{nhc}	Number of non-holonomic constraint
L_{EL}	Lagrange function
T_{EL}	System total kinetic energy
V_{EL}	System total potential energy
J_{el}	Performance index variable
ψ_{el}, C_{el}	Lagrange's performance constraint variables
ν_{el}	Lagrange multiplier terminal constraint constant
λ_{el}	Lagrange multiplier dynamics constraint function

$\dot{\lambda}_{el}$	Lagrange multiplier dynamics constraint function first derivative
μ_{el}	Lagrange multiplier path inequality constraint function
φ_{el}	Scalar value function
$H(\,)$	Hamiltonian system domain
r_{pGT}	Satellite perigee radius term used in Green's theorem
X_{GT}	Satellite apogee radius reciprocal function term in Green's theorem
ξ_{GT}	Green's theorem surface region boundary
J_{GT}	Green's theorem cost function
σ_{GT}	Linear differential form function
I_{GT}, F_{GT}	Initial and final orbit state in Green's theorem
Σ_{GT}	Interior region of closed loop boundary
ω_{GT}	Two-form solution defining surface region in Green's theorem
t_{coast}	Formation coasting period
α_d	Deputy satellite phase angle
$t_{f_{1-impulse}}$	Single impulse maneuver total flight time to chosen site
$t_{f_{2-impulse}}$	Bi-impulsive maneuver total flight time to chosen site
$f_{impulse}$	True anomaly at impulse point
$\gamma_{impulse}$	Satellite flight path angle at impulse point
$E_{impulse}$	Eccentric anomaly at impulse point
e_i	Initial orbit eccentricity

e_f	Final orbit eccentricity
ω_i	Argument of perigee for initial orbit
ω_f	Argument of perigee for final orbit
M_{0i}	Satellite mean anomaly in initial orbit where impulse firing occurs
f_s	True anomaly of the observed site
p_i	Initial orbit semi-latus rectum
V_i	Spacecraft velocity vector at a specific transfer point in initial orbit
V_f	Spacecraft terminal velocity at a transfer point in final orbit
$r_{iapogee}$	Spacecraft apogee radius in initial elliptical orbit
γ	Satellite flight path angle
$\Delta\gamma$	Spacecraft flight path angle difference
a_{tnfr}	Semi-major axis of transfer orbit
f_f	Satellite true anomaly in terminal orbit
θ_{tgt}	Transfer orbit angle for the two-impulse in cotangential transfer case
λ_{tgt}	Cotangential transfer case intermediate variable
r_{cf}	Circular final orbit radius
r_{ci}	Circular initial orbit radius
r_{3a}	First bi-elliptical transfer orbit apogee radius
t_{xm}	Satellite total time for non-maneuvered flight
t_{ixm}	Total flight time from initial position to the specific latitude for non-maneuvering initial orbit

t_{fm}	Satellite total flight time in final orbit for maneuvered flight
Δt_{3p}	Time difference between maneuvered and non-maneuvered satellite flights
M_{2s}	Satellite mean anomaly in final orbit for the observed site
M_{2i}	Spacecraft mean anomaly in final orbit at impulse point
M_{1s}	Satellite mean anomaly in initial orbit for the observed site
M_{1i}	Satellite mean anomaly in initial orbit at initial time
f_s	True anomaly of the chosen site
ε	Sign function
u_s	Argument of latitude for the chosen site
ε_s	Sign function of the site
M_{fs}	Spacecraft mean anomaly for the site in final orbit
x	Relative position component in Cartesian coordinate
$\dot{x}$	Relative velocity component in Cartesian coordinate
$\ddot{x}$	Relative acceleration component in Cartesian coordinate
y	Relative position component in Cartesian coordinate
$\dot{y}$	Relative velocity component in Cartesian coordinate
$\ddot{y}$	Relative acceleration component in Cartesian coordinate
x_0	Relative position initial condition in Cartesian coordinate
$\dot{x}_0$	Relative velocity initial condition in Cartesian coordinate
y_0	Relative position initial condition in Cartesian coordinate
$\dot{y}_0$	Relative velocity initial condition in Cartesian coordinate

$k_1, k_2\ k_3$	Integration constants
α	Satellite formation phase angle
ϕ_{rr}, ϕ_{rv}	Component of Hill-Clohessy-Wiltshire (HCW) matrices
$\tilde{\imath}, \tilde{\jmath}, \tilde{k}$	Cartesian coordinate unit vectors
Δv_{lfs}	Leader-follower longitudinal separation delta-V
$\partial {v_0}^-$	Formation relative velocity moment before time $t = 0$
$\partial {v_0}^+$	Formation relative velocity at time instance after $t = 0$
Δv_h	Cross-track direction delta-V in chief's satellite LVLH frame
φ_c	Critical true latitudinal angle
Δv_{rp}	Perigee point radial-track direction delta-V in chief's satellite LVLH frame
Δv_{ra}	Apogee point radial-track direction delta-V in chief's satellite LVLH frame
η_f	Keplerian element variable
$\Delta v_{\theta p}$	Perigee point along-track direction delta-V in chief's satellite LVLH frame
$\Delta v_{\theta a}$	Apogee point along-track direction delta-V in chief's satellite LVLH frame
ΔV_{chief}	Chief satellite total sum of delta-V consumption
ΔV_{deputy}	Deputy satellite total sum of delta-V consumption
$(\psi_{gc}, \lambda_{gc})$	Latitude and longitude position in spherical geocentric coordinate system, respectively
$(\varphi_{gd}, \lambda_{gd})$	Latitude and longitude position in geodetic coordinate, respectively
R_{eq}, R_a	Earth's equatorial radius

R_{pol}, R_b	Earth's pole radius
e_E	Earth's eccentricity
${e_E}^2$	Second order Earth eccentricity
u	Parametric latitude angle
OCA_{clo}	OCA for concentric-like overlap configuration
λ_{smc}	Smaller circle Earth central angle
OCA_{outer}	OCA for the outer region of multiple boundary overlap formation configuration
OCA_{inner}	OCA for the inner region of multiple boundary overlap formation configuration
OCA_{mbo}	Sum of OCA for the multiple boundary overlap configuration
A_{lune}	Overlap boundary area produced by two overlapped small circles
β_{ssp}	Subsatellite point difference angle
λ_i	Earth central angle for the ith satellite overlapped ($i = 1,2, \dots m$)
θ_{int}	Sum of the interior angle of a spherical polygon
n_p	Number of points defining an overlap region
f_d	Formation distance
f_a	Formation altitude
f_i	Formation inclination
λ_c , λ_d	Chief and deputy satellite Earth central angles
λ_{form}	Satellite formation Earth central angle

ε_{form}	Formation elevation angle
β_{form}	Angle between spacecraft's sub-satellite point over the ground
β_{form_max}	Maximum angle between spacecraft's sub-satellite point
AOC_{max}	Maximum ground area of coverage
D_{max}	Maximum ground swath length
(ϕ_c, λ_{ch})	Chief subsatellite point coordinate over true Earth ellipsoidal model
(ϕ_d, λ_{de})	Deputy subsatellite point coordinate over true Earth ellipsoidal model
f_{ell}	Flattening factor
n_3	Third flattening
e'_E	Second eccentricity
α_{er}	Reference azimuth angle measured from the Earth's ellipsoid model equator
α_c, α_d	Chief and deputy satellite forward azimuth angles
β_c, β_d	Chief and deputy satellite reduced/parametric latitudes
σ_{sparc}	Spherical arc distance between two points over Earth's surface
ω_{sp}	Spherical longitudinal angle difference
s_{ell}	Arc distance over the Earth ellipsoid model surface
A_I, A_4, A_5 C_{1l}, C_{2l}, C_{3l}	Coefficients in Taylor series form
I_1, I_2, I_3	Integral function
$\varepsilon_{ell}, k_{ell}$	Expansion parameters

x_{ast},y_{ast} μ_{kny}	Astroid problem variables
s_{cd}	Relative geodesic between chief and deputy subsatellite points
N_{gs}	Node point
E_{gs}	Edge point
G_1,G_2	Graph plots

CHAPTER 1

INTRODUCTION

1.1 Satellite Formation Flying Background

The concept of satellite flying in formation has been revolutionizing the way the space missions are defined and managed. The on-going trends and numbers of current and future space missions revolve around the applications of spacecraft formation flying (FF) are well-summarized in [1]. To date, numerous missions utilizing on the FF technology have been established such as, the Gravity Recovery and Climate Experiment (GRACE) [2], TANDEM-X [3], Magnetospheric Multi-Scale (MMS) [4] and the PRISMA mission initiated by the Swedish space agency [5]. These flight-proven FF missions unveiled the vast potential of such technology for future advanced space explorations. Obviously, the dominance of FF concept over the traditional monolithic space platform can be well described by its redundant characteristics which effectively extending mission lifetime, enabling greater coverage, reducing system complexity, and lowering the risk of mission failure while minimizing the overall mission costs.

Within the context of Earth observation study, any mission adapting to an FF concept would most likely to optimize its ground performance measure output. Due to this, there is no doubt that the satellite formation flying application would be suitable for the mission where responsive ground monitoring task is urgently needed. Alternatively, instead of initiating a brand-new mission to cater for a specific demand which is costly and time-consuming, slewing the existing FF platform towards the desired ground spot area would be the best solution. So far, not many literatures emphasize on the usability of spacecraft formation flying for a ground responsive orbit mission. Like for instance, [6] and [7] conducted some preliminary studies on the responsive orbit mission subject by means of a single spacecraft application, while [8] attempted on designing a responsive orbit using some sort of computational method which employs multiple-objective evolution technique. Also, [9] compared different modes of propulsion systems available to determine the satellite reachability and fuel efficiency in the responsive mission for ground track analysis. Furthermore, the effectiveness of solutions to the responsive orbit problem for the accomplishment of specific ground area monitoring can be measured based on their characteristics of fast response or turnaround time, the minimum cost incurred, the excellent ground measure acquisition (e.g., large coverage and wide length) and the hybrid potential capacity for other tactical applications. On the other hand, [10] suggested the use of fractionated space architecture that will provide the solution to this problem. It should be emphasized that for most responsive orbit case studies conducted, the main objective is to optimize the total amount of fuel consumption during the entire mission duration.

As explained in earlier, the ground merit quality is also equally important as the orbital assessment to evaluate the FF responsive mission effectiveness. Features like the maximum area of coverage, the optimum swath length coverage, the minimum land coverage overlap area, and the duration of target area accessible time defined by the locus of coverage characteristics are some of the fundamental parameters defining the satellite ground performances. Since less priority is always given to this research area segment, it is indeed worthwhile to explore the full potential benefits that can be gained from the deployment of such mission. Finally, with the incurrence of minimum on-orbit fuel and optimal ground performance, the spacecraft formation flying responsive mission will likely be a huge success in the future.

1.1.1 Problem Statements

Normally, when a sudden unexpected distress event occurs, the time taken to respond to such a scenario is always a critical factor. In many cases, where rapid and consistent monitoring over the affected ground site is urgently demanded, the applicable reaction time is usually very slow, partly constrained by the lack of available and appropriate observation platform. Initiating and launching a new dedicated mission on the other hand, proved to be costly and time-consuming [11]. Other issues surrounding this new mission are long turnaround time to operation, prone to delay factor, high risk of failure and low mission success reliability [12]. Although good spatial and site temporal resolution are the prerequisite criteria for the mission, the application of single monolithic spacecraft operation cannot accommodate the requirements for much frequent site visits [13]. The disadvantages of a single satellite operation trigger the efforts to search for a better alternative solution.

In other circumstances, when an existing space platform has been selected to conduct the mission, the conflict arises as to how to choose for the most rightful satellite candidate in orbit to ensure that the whole mission would be a successful one. Typical issues associated with the platform search include the estimated total amount of fuel needed for orbital repositioning until the establishment in the final responsive orbit and the desired satellite initial orbit semi-major axis parameters. On top of these two parameters, the determination for an orbital transfer fuel amount is considered as an utmost priority as this parameter constitutes the largest propellant consumption that will affect the longevity of spacecraft operating life. Available literatures on this field of study, currently do not specifically emphasize on the problem of fuel optimization for any given responsive space mission. Instead, the solutions to the generalized cases of spacecraft fuel optimization problem are usually tedious, and require complicated mathematical skills to solve them [14].

In any occasion, the ground performance for a single spacecraft cannot be compared to that of the multi-satellite configuration performances. In reality, the single satellite application often suffers from major drawbacks like poor coverage area, low temporal resolution and obviously possess high chances of failure that may jeopardize the whole planned mission [15]. Although the concept of satellite flying in formation can resolves the problems associated with mono-satellite operation, the technical challenges involved for ideal positioning of these spacecrafts remain an ongoing study. Other than that, when employing satellite formation flying to cater for a dedicated responsive mission demand, the search for optimum ground characteristics such as the total coverage area, the overlap coverage area, the coverage swath length, and the relative geodesic become important issues to deal with. It turns out that those optimum criterias stated are actually derived from excellent spacecraft formation configuration flying at a specified minimum distance from each other, while operating at relevant altitude over the Earth and ideal orbit inclination angle, which later become the subjects to be solved in this case study.

Finally, all the issues brought up earlier need to be resolved effectively so that the mission will achieve its purposes and gain maximal benefits.

1.1.2 Motivations

The current trend of launching complex multi-tasking single-use spacecraft to accomplish multiple mission objectives is indeed inefficient, especially when viewed from the economic perspective and operational reliability. This standalone platform is just capable of offering limited spatial resolutions or a constrained area of coverage, though it is fully-equipped with a set of high precision instruments. On the other hand, utilizing a fleet of simple and redundant satellites will ensure better coverage of the ground. Those previously mentioned weaknesses, inspired mission designers to seek for better alternatives and solutions towards ensuring a successful mission.

In the meantime, existing techniques dealing with responsive mission problem caused engineers to solve complicated analytical models in order to find a solution. Normally, the method applies to determine the amount of fuel needed to execute the mission, tends to be tedious, time-consuming and often results in a single solution without choices. Therefore, to overcome all these problems, a much simpler and more modular approach to the solution determination must be found.

Technically, when it comes to searching for the desired satellite formation flying on-orbit performance, many issues arise. Factors like the minimum amount of delta-V required and the best possible configuration specified by the formation distance, altitude and inclination characteristics to achieve the optimal performances are some of the key important critical features to be sought after. In addition to this, the difficulty of deciding on the most ideal formation initial orbit semi-major axis parameter against the requirements for optimum formation ground coverage performances, is in fact, among the reasons that motivate the research in this thesis.

Finally, for a dual-satellite formation flying initiated for a responsive mission purpose, some desired characteristics will enable an optimum total delta-V transfer maneuver, while having good resolution of the specific ground site, and arrives over the site at the minimal allocated time demand. These are examples of requirements that need to be explicitly addressed and resolved. As a summary, the main motivation is to search for the overall best solution by addressing the problems and challenges faced as stated before, so that the case study scenario can be tackled effectively.

1.1.3 Simulation and Modeling

All simulations and modeling in this thesis were done using the MATLAB programming software developed by MathWorks. This software enables satellite formation flying orbital simulation to be conducted through the propagation of its individual spacecraft orbit. Such realistic simulation that mimics the real-world scenario can help mission designers to understand and identify the presence of any possible disturbance or influence that might affect the satellite trajectory in the orbit. In some ways, MATLAB also meant for solving complex analytical solutions, thereby allowing further analysis into the problem to be investigated. By right, attending to the solutions would partly reduce the overall costs of satellite mission. In our case study, MATLAB is used further to model most of the mathematical expressions derived to search for the optimal results to the problem.

Results compilation were also made using MATLAB data structure function, which enable for the construction of graphs. The ease of using MATLAB functions to plot multiple graphs simultaneously has largely assisted in expediting the search for an optimal final solution. Besides MATLAB, other softwares like Microsoft Excel, Word and Mathematica also have been used throughout the case study for data processing and analysis purposes. Finally, MATLAB indeed is a powerful numerical computation and graphical tool software, which helps in conducting swift data analysis with reliable prediction as well as good accuracy through a virtual environment simulation platform without having to invest in real physical prototypes or tedious testing and measurement processes.

1.2 Research Aims

In general, the aim of this research is to find solutions to the governing problems of the satellite formation flying responsive mission performance topic. To accomplish that, multiple modes of impulse thrust were tested to measure their effectiveness and suitability in delivering optimum performances. By neglecting all the effects of perturbations except for the Earth's gravitational attraction, all the possible options are navigated thoroughly for the desired mission criteria and specifications before final decision is made. These outputs include all the best settings for a formation mission to operate in terms of the formation initial orbit semi-major axis preference, the total turn-around time prior to mission establishment, the fuel consumption and the satellite ground performance figure-of-merits.

Particularly, there are several main objectives that need to be accomplished throughout this research works which are:

i. To determine the global minimum delta-V amount for the formation transfer maneuver besides acquiring the local minimum delta-V values for each mode of impulses demonstrated through the application of novel graph analysis method.
ii. To investigate and measure the ground performance merits for a satellite formation flying responsive mission by means of several key parameters which are the maximum area of coverage, the overlap coverage area, and the maximum ground swath length distance.
iii. To study the properties and effects of the formation flying relative geodesic by varying their formation distances and altitudes.

1.3 Scope of the Study

The research conducted in this thesis focuses on analyzing the performances of satellite formation flown on a responsive space mission. Particularly, their performances are measured both in terms of on-orbit features and ground merit characteristics. By distinguishing the resulting trends and relationships that exist between variables found in each segment of study, this would enable us to decide on the best possible settings for the satellite formation to operate in order to achieve our mission objectives.

Specifically, investigations into the desired properties of the on-orbit satellite formation which revolves around the subject for determining the amount of fuel needed to execute each phase of the flight were conducted. The direct correlation trend between the amount of fuel consumed and the variability of formation distance parameter shall be revealed by the resulting graphs. These graphs were analyzed in details to validate the hypotheses. Apart from that, special focus shall also be given to determine the amount of orbital transfer fuel necessary which is the most crucial parameter throughout the research study. We shall demonstrate various modes of finite-based impulse application during satellite formation orbital transfer simulation to explore the possibility of obtaining the fuel optimal condition scenario. Next, the results yield from the graphs were further analyzed to identify the presence of specific signatures that point to the optimal fuel solutions. In connection to this, the relationship of other parameters such as the assigned formation initial orbit semi-major axis, the total turn-around time until the mission establishment and the number of required orbit revolution to the main working variable were also highlighted to supplement our research findings.

As with the ground segment performance, several important variables such as the formation maximum area of coverage, the overlapped coverage area and the swath length of coverage were analyzed in details. These parameters are very critical towards the acquisition of the optimal ground area of coverage. The graphs employing such variables were constructed against varying factors of the formation distances, altitudes and orbit inclination angles. By doing the cross-reference study, this allows the designers to assess information on the most ideal formation ground requirements, which aims at maximizing the acquisition of the total land coverage area and having the longest possible ground swath length while minimizing the overall effect of the ground coverage overlap. On the other hand, the formation-related geodesic properties were also investigated in this thesis. The contributing factors and their significant effects towards the accuracies of actual distance measure were rectified and elaborated further. Finally, all the results obtained were compiled and the conclusions on the best recommended performance settings for the satellite formation flying responsive mission were made.

1.4 Outline of Thesis

This thesis comprises of six main chapters namely, the introduction, the literature review, the theoretical modelling, the research methodology, results and discussion and finally, the conclusion section. In Chapter 1, the research problems and the goals to accomplish the objectives are defined. Chapter 2 provides detailed insights into all related research topics that include their historical reviews and some analytical derivations on the specific research topics. This section serves as the fundamental guidance towards understanding of the development in research areas to be studied. These study topics are the satellite formation flying, the responsive space mission, the spacecraft fuel optimization, the satellite geodesy, the spacecraft performance merits and the graph matching technique analysis. In Section 3, the appropriate analytical approximated solutions for the selected case studies are modeled and derived. After that, Chapter 4 briefly discusses the research methodologies used for carrying out such studies. When the case studies are completed, data analysis follows after. Chapter 5 disseminates all the outcomes resulting from the simulations of analytical models. These findings were discussed, and the decision was made based on the results to acquire the case study optimal performances. In the end, Chapter 6 concluded all the achievements made in solving the case study problems while specifying the research novelties and contributions. Additionally, some recommendations were also suggested for future works on some research areas.

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