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Satellite Conceptual Design Multi-Objective Optimization Using Co Framework

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This paper focuses upon the development of an efficient method for conceptual design optimization of a satellite. There are many option for a satellite subsystems that could be choice, as acceptable solution to implement of a space system mission. Every option should be assessment based on the different criteria such as cost, mass, reliability and technology contraint (complexity). In this research, mass and technology constraints, which have a direct impact on the satellite life cycle cost, are considerd as system level objective function to obtain the system optimal solution during the coceptual design phase. The approach adopted in this paper is based on a distributed collaborative optimization (CO) framework. At system level, multiobjective optimization goal is to minimize the dry mass of the satellite and, simultaneously, minimize the system technology complexity which is subject to equality constraints. The use of equality constraints at the system level in CO to represent the disciplinary feasible regions, introduces numerical and computational difficulties as the discipline level optima are non-smooth and noisy functions of the system level optimization parameters.To address these difficulties robust optimization algorithms such as genetic algorithms (GA) are used at the system level. The results show that the CO framework has the same level of accuracy as the conventional All-At-Once approaches.

Keywords: Design optimization, multiobjective, collaborative optimization, satellite conceptual design, genetic algorithms.

Nomenclature

CO	Collaborative Optimization
GA	Genetic Algorithms
AAO	All- At-Once
MDO	Multidisciplinary Design Optimization
MDF	Multiple Discipline Feasible
IDF	Individual Discipline Feasible
BLISS	Bi-Level Integrated Synthesis
CSSO	Concurrent Subspace Optimization
ATC	Analytical Target Cascading
GEO	Geosynchronous Earth Orbit
STEPS	Ship Tracking And Environmental Protection Satellite
MDB	Mission Design Block
SDB	System Design Block
ICE	Integrated Concurrent Engineering
PAN	Panchromatic Imager
C&DH	Command And Data Handling
GPS	Global Position System
AI&T	Assembly, Integration And Test
MT	Material Trade Off
CT	Configuration Trade Off
AHP	Analytic Hierarchy Process
PPT	Peak Power Tracking
DET	Direct Energy Transmission
SQP	Sequential Quadratic Programming
LEO	Low Earth Orbit

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Introduction

Most real-word design problems are actually complex and multidisciplinary with almost more than one objective function to be analysed simultaneously[1]. Those objective functions are often conflicting and non-commensurable, such as decreasing mass and technology complexcity in satellite conceptual design problem. Over the past two decades, there has been significant progress in the application of Multidisciplinary Design Optimization (MDO) to solve such complex design problems. Several MDO approaches have been proposed that include Multiple Discipline Feasible (MDF) [2], All-At-Once (AAO) and Individual Discipline Feasible (IDF) [3], Collaborative Optimization [4], Bi-Level Integrated Synthesis (BLISS) [5], Concurrent Subspace Optimization (CSSO) [6] and Analytical Target Cascading (ATC) [7]. Collaborative optimization is second-level optimization method proposed for solving multidisciplinary optimization design problem of a complex system [8][9]. The design of satellite system is a multidisciplinary coupled and complex design process, which means the design process involves multiple disciplines [10]. During the design course, the complexity of space environment task needs, the structure and function of the satellite gave tremendous challenge to the design. On the other hand, the design of space systems is a multidisciplinary process with multiple and often conflicting objectives such as cost and reliability. This is combined with the increasing demands of economic competition and complexity of space systems that has led to the rapid growth of the MDO over the past two decades [11]. The design of such complex systems traditionally involved a conceptual design phase, a preliminary design phase and a detailed design phase. For example, in the design of a satellite, the most important and crucial decisions in a space mission life-cycle are made during the conceptual design phase. This initial design phase offers the best opportunity to make radical changes preventing potential failures and anomalies before proceeding to detailed design phase and verification of the satellite design [12]. The conventinal sequential approach to such complex satellite system design involves a large number of iterations and generally leads to solutions very much dependent on the simplified initial assessments. However, it does not guarantee achieving the best compromise and may even lead to a non-optimal design. In the past years, several research works have been focused upon the use of the conventional optimization techniques to the conceptual design of satellite. For example, in the reference [13] the satellite optimization design based on normal cloud model was done for payload and power supply subsystems. The size of other satellite subsystems are calculated by experimental and the historical data. In this research the system level objective function is to minimize mass of the satellite. Byoungsoo [14] used meta-heuristic algorithms to minimize total cost of space system development based on the choice of technology at conceptual design phase in AAO framework. Hassan [15] applied multiobjective design optimization method using genetic algorithms (GA) for conceptual design of GEO satellite communication system. She has considered the satellite cost and reliability as system level objectives. In reference [16] conceptual design of the Ship Tracking and Environmental Protection Satellite (STEPS) is optimized in AAO framework. Also, Magnin [17] has presented a method for performing multiobjective optimization under the uncertainty of satellite systems.The objective of the research is to develop a method that combines a multiobjective MDO algorithm with a method for propagating and mitigating uncertainties. In another work, design optimization of a remote sensing small satellite mission has been performed using genetic algorithms whitin CO framwork [18]. Recently, a research is carried out on the applicaction of parallel simulation on a remote sensing satellite system design using eperimental data and ground stations requirments [19]. Collaborative Optimization Method

CO is designed in such a way that it supports disciplinary autonomy while maintaining inter-disciplinary compatibility thus providing additional design flexibility. These features make CO well suited for use in a practical multidisciplinary design environment such as space systems. CO has also been widely used to solve various complex multidisciplinary design problems including; launch vehicle design [20], aircraft design [21] and undersea vehicle design [22].

The transformation of the original coupled MDO problem into a CO framework is shown in Figure 1. It can be seen that the problem is hierarchically decomposed along disciplinary analysis boundaries into N disciplinary optimization problems. The design variables and constraints of the original problem are partitioned as shown in Figure 1.

The system level optimizer is used to minimize the system level objective function (design objective function) while satisfying consistency requirements among the various disciplines by enforcing equality constraints at the system level ($gi^* = 0$, $i=1,\ldots,N$).

For example, S_i is a vector of subset of S composed of all variables, which affect discipline i. The system level variables are treated as fixed parameters in disciplinary optimization runs.

Thus, the role of each disciplinary optimizer is to minimize, in a least squares sense, the discrepancy between the disciplinary design variables and target values provided by the system level optimizer. The number of equality constraints (N) is related to the number of the disciplines. CO is posed in a hierarchical structure and in comparison with a nonhierarchical system is advantageous due to its parallelization, lack of iteration requirements between disciplines and organizational characteristics. These features make CO well suited for use in a practical multidisciplinary design environment. However, due to complex interdisciplinary couplings, which are inherent in MDO

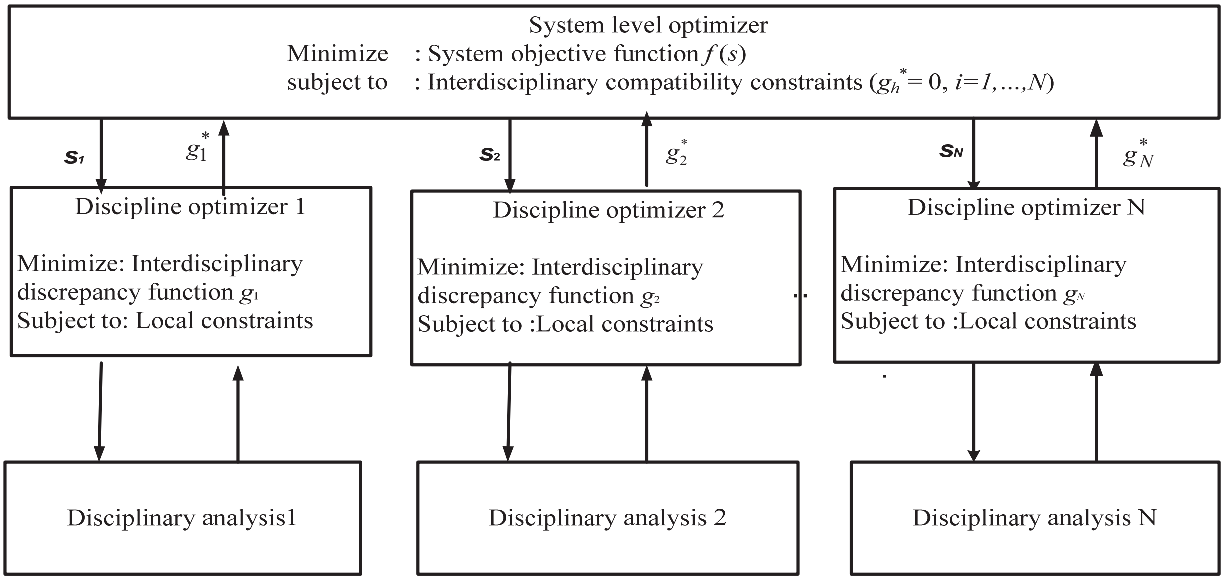

Fig. 1 Collaborative optimization framework

problems, it results in a very high overall computational cost, limiting real-life applications of CO method. In addition, the equality constraints at the system level introduce some numerical features that hinder the direct application of gradient-based optimization algorithms at the system level within CO framework [18]. To address these challenges, the remainder of this paper focuses upon the implementation of a robust GA algorithm for solving optimization of remote sensing satellite design within distributed CO framework.

Framwork of Multiobjective Optimization

In the satellite multiobjective design optimization, multiobjective optimization has been defined as finding a vector of design variables satisfying constraints to give acceptable values to all objective functions. In general, it can be mathematically defined as:

$$\text{Min } F(x)=[f_1(x), f_2(x), \dots, f_k(x)]^T \quad (1)$$
$$\text{s.t } g_i(x) \le 0 \quad (i=1, \dots, l) \quad (2)$$
$$h_i(x) = 0 \quad (i=1, \dots, m) \quad (3)$$
$$x_{i,low} \le x_i \le x_{i,up} \quad (i=1, \dots, n) \quad (4)$$

where $x=[x_1, x_2, \dots, x_n]^T$ is the vector of design variables; $g_i(x) \le 0$, $(i = 1, \dots, l)$ are the inequality constraints; $h_i(x) = 0$, $(i = 1, \dots, m)$ are the equality constraints. $x_{i,low}$ and $x_{i,up}$ define the lower and upper bounds for the i^{th} design variable and x_i respectively; $F(X)$ is the vector of objective functions, which must be either minimized or maximized. Without loss of generality, it is assumed that all objective functions are to be minimized. A maximization type objective can be converted to a minimization type by multiplying negative one [1].

Remote Sensing Satellite Design Model

The satellite system design problem comprises two levels, namely mission design block (MDB) and system design block (SDB). The MDB block performs mission analysis and design based on the mission and customer requirements. The SDB block is divided into various subsystems (disciplines). These disciplines are designed based on the analysis data provided by the MDB block and the deisgn data interact with each other (for more details see reference [23]).

The general objectives of the mission include geographical mapping, natural disaster assessment and environmental monitoring. Requirements driving the design include a mission duration of 3 years, an orbital altitude of less than 600 km and inclination in the vicinity of 55°.

The satellite design process was conducted using the integrated concurrent engineering (ICE) process. Physics-based models were developed for each subsystem in the conceptual design. Over 50 core equations, hundreds of sub-core equations, and ~300 parameters are used in total to represent the satellite. Disciplines of the satellite conceptual design model are shown in Table 1. The disciplines listed in Table 1. are all strongly coupled to each other in typical conceptual-satellite design. This coupling complicates the interaction during the design process and creates competing demands to optimize individual subsystems at the expense of the total satellite.

Model Description

Since the satellite conceptual design model is a recursive function, it must be solved iteratively. The satellite discipline order in the iteration loop is based on how the disciplines interact. The iteration loop is said to converge when the difference in satellite dry mass from the previous iteration and the current iteration is less than a predefined quantity, termed the mass criterion. In this study, a function evaluation is defined as the evaluation of the model until convergence to the mass criterion is achieved. In this research the mass criterion is set at 0.5kg.

Table 1. Disciplines of the satellite conceptual design model

Discipline	Description
1. Mission Design	Defines operating modes and mission phases; characterizes all aspects of launch and orbit; determines velocity changes necessary to achieve and maintain orbit
2. Payloa	Instruments and devices used to achieve the mission goals
3. Attitude Determination & Control System	Receives and transmits signals between the satellite and ground stations on the Earth
4. Telecommunications	Orients and stabilizes the satellite for specific events countering external and internal disturbances that act upon it
5. Command & Data Handling	Stores and processes commands and data
6. Power	Generates, conditions, regulates, stores, and distributes power throughout the satellite
7. Structures & Mechanisms	Supports and protects all other subsystems for all operating modes of the satellite in all of the expected mission phases; deploys components and/or separates them from other elements during the mission
8. Thermal Control	Maintains all components of a satellite within their allowable temperature limits for all operating modes of the satellite and in all of the expected thermal environments

In the traditional integrated concurrent engineering process, engineers monitor and adjust their subsystem models in each iteration in order to ensure that their design decisions are, at a minimum, feasible. Due to the large number of iterations involved in the optimization analysis, this sort of human interaction is impossible [24]. Hence, an input vector is defined for each of the 8 disciplines where some of the inputs are fixed (known) values, some are from other disciplines, and the remainder are optimizable. Most of the simplifying assumptions made in the development of this model are justifiable since the application is for early-stage conceptual design at which point a rigorous analysis with detailed models is not performed. The primary goal of a conceptual design is to ascertain the feasibility of the mission within the constraints defined by the requirements and possibly to suggest promising design configurations worthy of further investigation. If successful, a conceptual design results in additional funding to produce a more detailed (preliminary) design where more resources (e.g., people, more sophisticated models, etc.) are made available [24].

Mission Design

The mission design discipline calculates the ground station view durations, velocity changes, sun angle and orbit characteristics. In this discipline also the launch vehicle capabilities are counted as constraints. Simplifying assumptions includes limiting the orbit to one that is semi-circular with 55° inclination and representing the Earth as a perfect sphere. All orbit perturbations have been assumed as constant over the lifetime of the mission and calculated under worst-case conditions. All calculations are based on equations in Wertz & Larson [24].

Payload

The satellite payload consists of an imaging payload (panchromatic camera). The panchromatic imager (PAN) mass is estimated based on scaling equations given in Wertz & Larson [24] relating the assumed aperture diameter to an actual aperture diameter on a similar instrument used in a similar mission. The resolution of the PAN is determined based on equations given in Wertz & Larson [24]. The resolution of payload and swath are considered as design variables with lower and upper limits.

Structure and Mechanisms

The structural subsystem model determines structure masses, mechanism masses and satellite-bus dimensions. According to the launch vehicle axial and longitudinal loads and selected shape for the satellite bus, using exist relations, proper thickness of main structure, top and down decks, panels and intermediate ring with adaptor are calculated. Structure masses are computed based on the material density and thicknesses which are obtained previously. Moment-of-inertia calculations are performed under the assumption that the bus mass is uniformly distributed.

Command and Data Handling

The command and data handling (C&DH) subsystem model determines masses of the processor and solid-state recorder, power requirements, temperature tolerances, and onboard data-storage capacity. A significant assumption affecting this discipline is that component selection is dependent on the required data rate and data-storage capacity. Below a threshold data rate, the processor is classified as simple requiring less mass and power. An amount above this threshold is classified as complex, thus requiring greater power and mass. Similarly, a solid-state recorder is classified as small or large depending on the data-storage requirement and a data-storage threshold. All calculations for this discipline are based on Wertz & Larson [24].

Communication

The communication subsystem model determines communications specific component (e.g., antennas, filters, diplexers, transmitters, etc.) masses, power requirements and pointing requirements based on equations given in Wertz & Larson [24]. Simplifying assumptions include the use of a high-gain antenna for both data transmission and communicating engineering telemetry with ground stations.

Attitude Determination and Control

This subsystem model determines altitude determination component (e.g., horizon sensors, sun sensors, magnetic sensors, etc.), altitude control actuators for maneuvers (e.g., magnetorquers, reaction wheels, gravity gradient boom, etc.) and masses considering the mission requirements. Also, the model determines power requirements, and satellite pointing capabilities. To meet the satellite position knowledge requirement, a global position system (GPS) receiver is defined as a fixed component. A significant assumption with this subsystem is to model disturbance torques as time-independent.

Electrical Power Supply

The power subsystem model determines power specific component (e.g., batteries, solar array, distributor, etc.) masses, battery capacities, solar-array area, and component temperature tolerances. During the computations, as the solar array dimensions growth is more than the allowable space of launch vehicle fairing, deployable solar array option is chosen automatically. In this case, the solar arrays are assumed to be body-mounted. All calculations performed are based on Wertz & Larson [24].

Thermal Control

The thermal control subsystem model determines thermal specific component (e.g., radiator, heaters, etc.) masses, radiator area, and power requirements. View factors [24] are assumed for each of the satellite faces and energy balance computations are then performed. The model computes a worst-case maximum satellite temperature and sizes a radiator to ensure that an energy balance is achieved. A similar calculation sizes the heaters for the worst-case-minimum temperature. Hence, a significant assumption in the thermal analysis is that the temperature of the satellite is analyzed only at specific extreme-case intervals of the orbit.

Assessment of Technology Complexity

Today, design optimization objectives are exposed transitions in such a way that technology constraints achieve special role during preliminary design phases. For example, recent developments of Dassualt [25] are geared towards taking into account that the digital design environment must be integrated with distributed design and manufacturing teams, pushing research into creation of methods that can accommodate virtual design teams. Additionally, they are focusing on integrating manufacturing and downstream requirements into the MDO process. This is accomplished by using Lagrange multipliers, generated at the detailed design stage, to inform engineers involved with the preliminary design stage of important downstream constraints [26]. From this point, the system technology value is considered as one of the objective functions at system level optimization. The methodology of technology assessment is presented for structure subsystem, typically.

Test Case

In this section, trade off criteria are presented for defining important factors in the choice of structures material and configuration alternatives to have the system mission and constraints such as mass and strength. In the following, structures tradeoff alternatives based on the tradeoff goals (material alternatives: Aluminum, Steel and configuration alternatives: Cubic, Hexagonal, Cylindrical) with the weight, score and ranking of each are presented. Main criteria considered here are: Availability, AI&T (Assembly, Integration and test), performance and cost.

Each one of these criteria is divided to some sub-criteria; based on the trade off goals, as the following:

Availability: This criterion defines the availability level which includes:

- Procurement and manufacturing (Material Trade off (MT))
- Experience and manufacturing (Configuration Trade off (CT))

Assembly, Integration and Test (AI&T): Here AI&T shows the satellite assembly simplicity that includes:

- Harness, fasteners, flexibility and alignment (MT)
- Integration complexity, subsystem assembly complexity, fasteners and harness (CT)

Performance: This is one of the most important criteria in the design of layout of the subsystems. These criteria are:

- Stability, bounding, thermal, EMC/EMI (MT)
- Stability, power, volume and communication requirements (CT)

Cost: During the conceptual design phase, cost of the production based on the selected configuration should be considered. Here cost is considered as one of the most important criteria for subsystem trade off goal.

Tree view of structure material and configuration trade off and their related weights are shown in Figures 2 and 3.

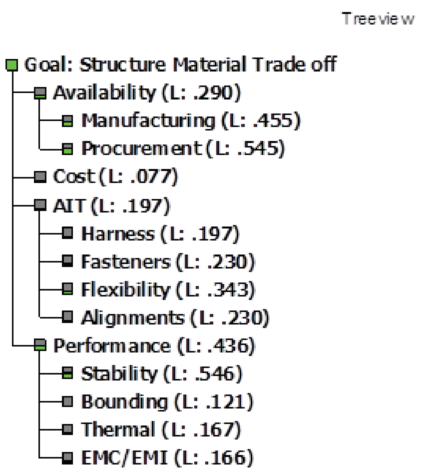

Fig. 2 Material trade off

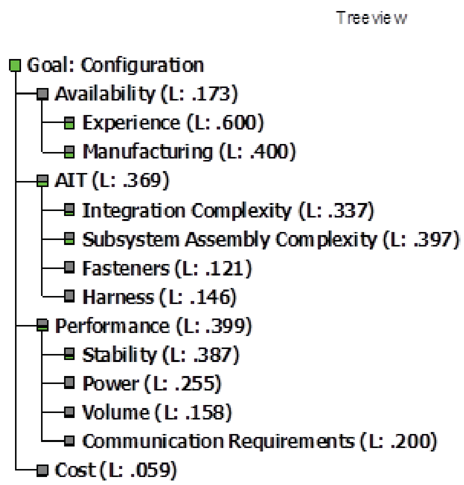

Fig. 3 Configuration trade off

that trade off goal. For structures tradeoff alternatives in line with the tradeoff goals, the technology value which is obtained from Analytic Hierarchy Process (AHP) approach [27] is presented in Figures 4-5.

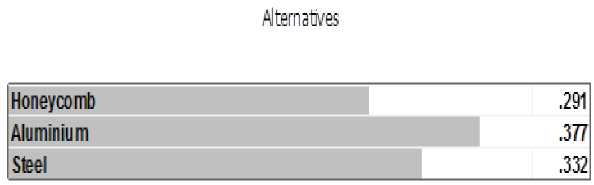

Fig. 4 Technology value of design alternative for material trade off

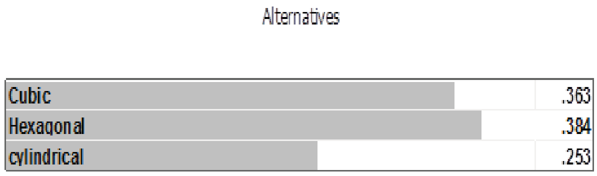

Fig. 5 Technology value of design alternative for configuration trade off

These scores of each of the design alternatives for other subsystems obtained from similar approaches are implemented in design calculations.

The Problem Optimization Formulation

In the satellite conceptual design problem, eight disciplines (Table 1) are used to demonstrate the proposed methodology. In this case there are two objectives which are in paradox. In fact the problem deals with the minimization of the satellite mass and maximization of system feasibility (or minimization of technology complexity) subject to design constraints as well as the side constraints on the design variables. The satellite design optimization involves twelve (discrete and continuous) design variables. Continuous design variables related to the payload discipline and discrete design variables related to the bus trade options are considered as design vectors. The design data for the satellite design problem including design variables, assumptions and known quantities used in this study are shown in Table 2. For some disciplines, weight characteristics are obtained from parametric correlations [24].

Implementation of the Problem within CO

The satellite conceptual design problem described in Section 3 is now implemented within a distributed collaborative optimization framework. The problem is decomposed into the disciplines and a system level optimizer to coordinate the overall optimization procedure.

Table 2. The problem design data

Design data				
Design Variables				
Continuous	Discrete		Assumptions	Known Quantities
	(Trade Option / Trade Parameters)			
Payload	Structure		Mission	Orbit
Elevation Angle	Configuration	Panel Elevation	Year of Launch	Gravitational Constant
Ground Resolution	Material	Mod. of Elasticity	Mission Lifetime	J2
		Poisson Ratio	Mission Class	Earth Radius
		Density	Schedule	Earth Angular Rotation
		Strength	Launch Vehicle	Earth Rotation
	Attitude Determination & Control (ADCS)		Orbit	Velocity
	Actuators	Max. Momentum	Altitude	Payload
		Torque	Inclination	Speed of Light
		Comp. Mass	Ascending Node	Planck's Constant
		Comp. Power	Payload	Boltzmann's Constant
	Control Scheme	Accuracy	Instrument Class	Sub-angle of Sun
	Determination	Comp. Accuracy	Detector Type	Electric Charge
	Components	Comp. Mass	Telescope Type	Earth Radius
		Comp. Power	Wavelength Region	BB Temp of Sun
	Communications (Comm.)		Change in Reflectance	BB Temp of Earth
	Antenna Type	Efficiency	Instrument Duty Cycle	Reflectance
		Mass	Structure	Atmosphere Trans.
	Modulation	E_bN_o	Ultimate Factor of Safety	Structure
	Command and Data Handling (C&DH)		Yield Factor of Safety	Drag Coefficient
	Complexity	Data Rate Limit	ADCS	Magnetic Dipole
		Radiation Limits	Reflectance	ADCS
	Mass Storage	Capacity	Torque Margin Factor	Atmospheric Density
		Volume	Comm.	Magnetic Field at Poles
		Power	Frequency	Comm.
	Thermal		Comm. Elevation Angle	Transmitter Line Loss
	Control		Bit Error Rate	Implementation Loss
	Coating Material	Emissivity	Link Margin	Thermal
		Absorbance	Grnd Station Latitude	Earth IR Emission
	Power		Grnd Station Longitude	Albedo
	Regulation	Efficiency	Grnd Station Ant. Dia.	Solar Flux
	SA Material	Efficiency	C&DH	
		Degradation	Number of Bits/ Sample	
		Sp. Performance	Thermal	
	Battery Type	Sp. Performance	Radiator Lower Limit	

Design data					
		DOD		Power	
	Deployable			Inherent Degradation	
				Transmission	
				Efficiency	

Here collaborative optimization formulation of the problem is presented. Trade options of design variables (see Table 2) are also presented in Table 3. The lower and upper bounds of design variables and suggested values for each of them as initial conditions are shown in Table 4.

Table 3. Trade off alternatives of design variables

Variable	Trade off Alternatives
X_1	Continuous
X_2	Continuous
X_3	Aluminum, Steel
X_4	Box, Hexagon, Cylinder
X_5	sun sensor, Magnetometer, GPS, Horizon sensor, Gyro
X_6	Boom, Magnetorqure, Momentum wheel, Reaction wheel
X_7	Horn, Helix, Parabolic reflector
X_8	QPSK, FSK, BPSK
X_9	PPT, DET
X_{10}	Silicon, Gallium Arsenide, Multi Junction
X_{11}	Nickel Cadmium, Nickel Hydrogen, Lithium Ion
X_{12}	White epoxy, White enamel, Black paint, Teflon, Aluminum

At a satellite multiobjective design optimization, the problem has been defined as finding a vector of design variables satisfying constraints to give acceptable values to all objective functions. The formulation of the system level can be expressed as below:

Minimize: $F(x)=[f_1(x),f_2(x)]$ (5)

f_1: Satellite mass

f_2: System technology complexity

Subject to:

$g_1^*=0,\ g_2^*=0,\ldots,\ g_8^*=0$ (6)

$86.2 \le S_1 \le 88.8$ $\quad 25 \le S_2 \le 50$

$S_3=[0,1]$ $\quad S_4=[0,1,2]$

$S_5=[0,1,2]$ $\quad S_6=[0,1,2,3,4]$ (7)

$S_7=[0,1,2]$ $\quad S_8=[0,1,2]$

$S_9=[0,1]$ $\quad S_{10}=[0,1,2]$

$S_{11}=[0,1,2]$ $\quad S_{12}=[0,1,2,3,4]$

Table 4. Design variables lower and upper bounds

Variable	Variable Name	Lower Bound	Suggested Value	Upper Bound
X_1	Instrument Elevation Angle	86.2	87.5	88.8
X_2	Ground Resolution	25	30	50
X_3	Material Trade Choice	0	0	1
X_4	Configuration Trade Choice	0	1	2
X_5	Determination Trade Choice	0	1	2
X_6	Actuator Trade Choice	0	2	4
X_7	Antenna Trade Choice	0	1	2
X_8	Modulation Trade Choice	0	1	2
X_9	Regulation Trade Choice	0	0	1
X_{10}	Solar Array Trade Choice	0	2	2
X_{11}	Battery Trade Choice	0	1	2
X_{12}	Thermal Material Trade Choice	0	2	4

The system level continuous design variables s_1 and s_2 represent instrument elevation angle (ε) and imaging payload resolution (R), respectively. s_3 to s_{12} are the system level discrete design variables presented in the Table 3. These are treated as system level target values (shared design variables) corresponding to discipline level design variables. g_1^* – g_8^* are the system level equality compatibility constraints (for more details, see reference [1]).

Optimization Algorithms

For solving the problem, GA optimization algorithms are studied for both the discipline and system levels optimization. As discussed earlier in the paper the constraints at system level are equality (discrepancy function $g_i^*=0$, i=1, 2.., 8) and have a complex form as compared to constraints at discipline levels. Their values correspond to a measure of disagreement between the targets given to a discipline by the system level optimizer. The values of these constraints are obtained by solving disciplinary optimization problems. These values (system level constraints) are generated by optimization and hence they are non-smooth at the transition from a plateau of zero values to a region of non-zero values (for further details, see reference [28]). Therefore, derivative-based optimization algorithms such as sequential quadratic programming (SQP) cannot be used at system and subsystem levels. In order to overcome these difficulties, a more robust optimization algorithm, GA, is used in this optimization process.

For solving the problem, initially, the alternatives of each subsystem are selected by genetic algorithms and enter the satellite conceptual design model as design variables vector. At the mission discipline, mission and orbital characteristics for defined orbits (sun synchronous and other orbits) are calculated. Then main loads which are imposed on the main structure are determined. Based on the input variables and launch vehicle specifications, mass of structure is primarily calculated. Computations for each subsystem are done using input design vectors and the satellite mass is computed in an inner loop. The computed mass is considered for the next loop until the convergence criterion is satisfied. Final mass with final value of technology complexity, which is obtained for each discipline (section 3.2), are sent to the system level. After assessment of the system level objectives, new design vector is randomly generated and the described procedure is repeated to obtain the optimal solution. According to the alternatives that are established for each subsystem, the space design includes about 70000 options as the problem solutions.

Result Analysis

In this research the satellite weight and technology constraints have been considered as the system level objectives. Both objectives have considerable roles on the satellite life cycle cost; whilst there are two objectives which are in paradox.

For solving the optimization problem, both conventional (All-At-Once) and collaborative optimization frameworks are implemented using GA algorithm. The tuning parameters used in GA algorithm (population size 40, mutation rate 0.5 and re production scheme: roulette wheel). First, the problem is solved with AAO framework for only one objective function (the satellite weight) subjected to the design constraints. Results of optimization are shown in Table 5.

A weight factor β is defined, for assessment of the system level objectives effect on optimum design solution. For evaluation of the methodology, the problem was run using both AAO and CO frameworks for mass-based (β=1.0) and technology-based (β=0.0) design optimization. The satellite system specifications which are obtained from both design strategy are presented in Table 6.

After evaluation of the methodology, optimum design solutions for defined design vectors (e.g. technology configuration) have been obtained for mass-based and technology-based goals using AAO and CO frameworks. All disciplinary constraints are satisfied and the results are shown in Table 7.

Table 5. Results of optimization (All-At-Once) using GA

Variable		Optimum solution
Design variables	X_1	88.6
	X_2	50
	X_3	Aluminium
	X_4	Cylindrical
	X_5	Sun sensor, Magnetometer, GPS
	X_6	Magnetorqure, Reaction Wheel
	X_7	QHA
	X_8	FSK
	X_9	DET
	X_{10}	Multi-junction
	X_{11}	Li-Ion
	X_{12}	Black Paint
Objective function	Satellite weight (kg)	42.5

Table 6. The satellite system specifications

System Specification	CO Opt. β = 0.0	CO Opt. β = 1.0	AAO Opt. β = 1.0
Satellite Weight (Kg)	79.5	43.3	42.5
Revisit Time (Day)	66	67	67
Resolution(m)	50	50	50

Table 7. Results using AAO and CO frameworks

	Solution \ Framework	All-AT-Once Optimization Technology-based	All-AT-Once Optimization Mass-based	Collaborative Optimization Technology-based	Collaborative Optimization Mass-based
Technology Configuration	Main Structural Material	Aluminium	Aluminium	Aluminium	Aluminium
	Main Structural Configuration	Hexagonal	Cylindrical	Hexagonal	Cylindrical
	Attitude Determination Components	Magnetorqure, Momentum Wheel	Sun-sensor, Magneto-meter, GPS	Magnetorqure, Momentum Wheel	Sun-sensor, Magneto-meter, GPS
	Attitude Control Actuators	Magnetorqure, G.G. Boom, Momentum wheel	Magnetorqure, Reaction Wheel	Magnetorqure, G.G. Boom, Momentum wheel	Magnetorqure, Reaction Wheel
	Antenna Type	QHA	QHA	QHA	QHA
	Modulation	QPSK	FSK	QPSK	FSK
	Regulation Scheme	PPT	DET	PPT	DET
	Solar Cell Type	Multi-junction	Multi-junction	Multi-junction	Multi-junction
	Battery Type	Ni-Cd	Li-Ion	Ni-Cd	Li-Ion
	Thermal Coating	Black Paint	Black Paint	Black Paint	Teflon

According to the results which are presented in Table 7, when a designer pay more attention to the technology aspects (i.e., 1-β= 0.8), in fact items such as availability, cost, performance and AI&T attain more importance for decision making. In this case the obtained solution for conceptual design problem has no technology complexity; however, this reduction in complexity results increase in the satellite mass. Weight of the payload has direct effect on the launch execution cost. On the other hand, when the system mass has been more important as compared with the technology constraints (i.e., β=0.8), mass of the satellite would be very low but the solution may involve technology difficulties.

Conclusion

This paper described collaborative multidisciplinary multi-objective optimization for remote sensing small satellite conceptual design in LEO. In this approach, the design optimization problem of the satellite is divided into system and discipline levels. The discipline level involves subsystems such as

payload, electrical power supply, altitude determination and control system, communication, thermal control system, structure and command, and data handling. The objective function was the minimization of the satellite mass and, simultaneously, minimizing the system technology complexity. Coordination of disciplinary optimization process was carried out at the system level. Due to the peculiar characteristics of the equality constraints at the system level, a robust GA algorithm is used at the system level. In this research, a function evaluation is defined as the evaluation of the model until the convergence to the mass criterion is achieved.

To evaluate the satellite conceptual design model, the problem was solved using AAO framework for only one objective function subjected to the design constraints (Table5).

After evaluation of the methodology, the problem was also implemented within a collaborative optimization framework and optimum design solutions were obtained for different weight factor, β, using both AAO and CO frameworks (Table7). According to the results (Table 7), as technology aspects have enjoyed more importance in the optimization process, the satellite mass increases greatly. On the other hand, minimization of the satellite mass results in growth of the system complexity. Thus, selection of the weight factor for each of the optimization goals at system level is affected by design strategy and the system engineer opinion during the project design phase.

The results obtained show that the CO based on GA adopted in this paper has the same level of accuracy as the conventional all at once approaches (Table 6); however, the proposed approach provides potential for solving complex multidisciplinary design problems such as spacecraft system design optimization under uncertainty where it would be difficult or very time-consuming using conventional all at once approaches.

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