HETEROGENEOUS CONSTELLATION DESIGN METHODOLOGY APPLIED TO A MARS-ORBITING COMMUNICATIONS AND POSITIONING CONSTELLATION

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HETEROGENEOUS CONSTELLATION DESIGN METHODOLOGY APPLIED TO A MARS-ORBITING COMMUNICATIONS AND POSITIONING CONSTELLATION

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This research develops software that applies model-based systems engineering design optimization to the problem of satellite constellation design. The software uses a genetic algorithm solver to generate and evaluate candidate solutions to a set of user-defined missions given allowable ranges of satellite and orbital parameters. The methodology allows for the comparison of single-satellite constellations and disaggregated heterogeneous constellations. As a sample case, the problem of designing a Mars-orbiting position, navigation, timing, voice communications, and data relay constellation is examined. The optimization determined that a highly inclined Walker Delta constellation of forty-five multifunction satellites was the best solution.

INTRODUCTION

With the increasing popularity of small, micro, and nanosatellites, the economic and performance viability of launching several satellites to do a task hitherto performed by a single large satellite is increasing. Traditional constellation design methodology and tools are not equipped to compare the performance of a typical constellation of identical satellites to the performance of a heterogeneous constellation, which is comprised of satellites of different capabilities. In such a constellation, mission objectives and payloads may be divided among several satellites instead of being aggregated on a single satellite. Also, large heterogeneous constellations of satellites can perform tasks involving machine learning, big data, and other large volume tasks that would be unfeasible for a single satellite. However, this disaggregation creates problems not only in orbit design but also in packaging and distribution of sensors, payloads, and satellites. The software created through this research uses a new model-based systems engineering design optimization to determine a near-optimal configuration of satellites to satisfy a variety of user-defined missions. As a test case, the software is tasked with generating a Mars-orbiting constellation that provides voice communications, positioning information, and data transfer to and from Earth to a hypothetical Mars colony.

This research is an extension of the disaggregated integral system concept optimization (DISCO) methodology introduced by Thompson.[1] DISCO has been applied to problems including the development of a disaggregated defense weather system as a follow-on mission to replace existing space-based weather assets, launch vehicle manifesting, and the creation of a space-based fire detection system.[2,3,4] This research implements a more accurate dynamics model for satellite propagation and increases mission variety.

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DISCO arose as a response to increasing interest in disaggregation, particularly multi-function disaggregation. Experiments and proof of concept flights have shown that nanosatellites can perform tasks such as space weather monitoring and beyond-line-of-sight voice communications.[56] Because these low-cost satellites create the possibility of replacing or augmenting older, larger satellites, it is necessary to be able to compare their performance and cost to that of a larger satellite in order to determine the best satellite for the task. As in the DISCO methodology, a genetic algorithm was chosen for this research to allow changing constellation size, to effectively span the search space, and to allow flexibility in system modeling. Genetic algorithms have been successfully evaluated for use in constellation design with various computing architectures.[7] This specific application uses an elitist genetic algorithm with the option of using variable length genomes.[8] Constraint handling is difficult with genetic algorithms, so currently constraints are checked prior to the evaluation step of the genetic algorithm and an attempt is made to correct the genome if it is found to violate a constratint.[9]

Interest in sending manned missions to Mars has increased in the last decade. Indeed, various organizations have declared their intent to perform a manned Mars mission within the next two decades.[1011] As manned missions to Mars increase, it will be necessary to have communications infrastructure available to support both planetary and interplanetary communications. The goal of this research is to produce not only an initial design of a Mars-orbiting communications constellation, but also provide a tool that allows repetition of the analysis as mission requirements and available technology change. Previous Mars constellation design efforts have focused on communications capabilities only and used traditional constellation design techniques with no optimization.[12] Other analyses determined the ability of a constellation to provide positioning information for an incoming spacecraft rather than for ground stations.[13] Furthermore, none of these analyses allow for the design of a heterogeneous constellation of satellites, which is the ultimate goal of this research, enabling a single tool to explore a wide variety of design spaces.

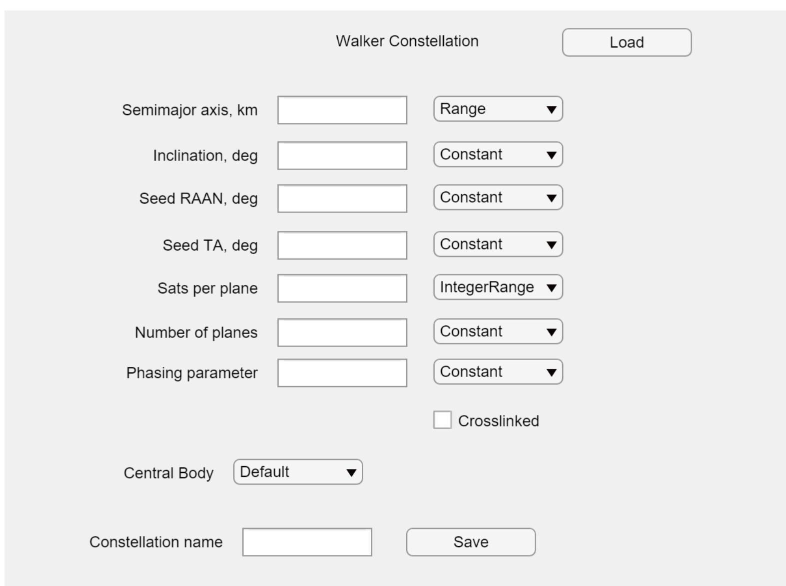

Figure 1. Walker constellation creation graphical user interface.

MODEL

A unique constellation modeling and optimization software was created as a result of this research. The software allows a user to define several types of assets to be assigned to the analysis, then calculates the ability of these assets to satisfy a specified mission or missions subject to constraints. A genetic algorithm optimizer is used to create the candidate solutions.

Assets

A graphical user interface (GUI) is used to create the assets in the mission analysis. Each asset type has a variety of properties that can be defined as constants or as variables to be controlled during the optimization. The Walker constellation creation portion of the GUI is shown in Figure 1.

Sensors and subsystems. Sensors and subsystems are intended to be used to build a satellite that has not yet been fully designed. Sensors and subsystems can be assigned dynamically to satellites and ground stations during the optimization routine. Currently implemented sensor types are transmitters and receivers. Transmitters have frequency, power, and either antenna half angle or gain properties. Receivers have either antenna half angle or gain properties. All transmitter and receiver properties can either be constant or variable. Future iterations of the software will include propulsion and power subsystems in addition to various sensor packages.

Ground stations. Ground stations are assigned a latitude, longitude, altitude, and central body. The ground station position is set as a constant by default but could be varied in order to find optimal ground station placement. Sensors are then assigned to ground station as either required or optional sensors. The inclusion of optional sensors is controlled by the optimizer.

Satellites. Because the purpose of this research is to allow users to compare the performance of satellites of varying levels of capability, the satellite definition stage is of critical importance. The satellite can be defined in one of two ways. The first method creates a satellite by defining values or ranges for properties such as transmission frequency, transmission power, data rate, and other relevant communication parameters. Because these factors are significant determinants in the size and cost of a satellite that does not perform specialized scientific tasks, varying them allows for the comparison of satellites in different weight and cost classes without requiring the user to define many types of satellites.

The second method of satellite definition is more general and can be used for any type of satellite, not just communications and data relay satellites. A satellite is created by assigning required and optional sensors and subsystems. Satellites of fixed capability and design can be created by requiring subsystems. However, the inclusion of optional subsystems easily enables the comparison of large multifunction satellites to combinations of smaller, less capable satellites. Consider a mission requiring three types of sensors. The mission could be accomplished with either a single satellite type hosting all three sensors or by three types with a sensor apiece. Other candidate solutions are the various combinations of one satellite type with two sensors and another with the third sensor. There are in total seven possible satellite types: three single function, three dual function, and one triple function. However, by using optional sensor assignment, the number of satellite types can be reduced to three. The first type requires the first sensor and allows the second and third as optional. The second type requires the second sensor and allows the third as optional. The third type requires the third. Because only three satellite types are necessary, the number of variables used in the optimization can be greatly reduced.

Constellations. Currently, two types of constellations can be created. The first is a Walker Delta constellation, which is a series of circular orbits of identical inclination and radius and varying longitudes of the ascending node. The size of the constellation determined by the number of planes and number of satellites per plane. Both the orbital and size characteristics can be varied. The second type of constellation is a single orbit described by eccentricity, semimajor axis, inclination, argument of periapsis, and longitude of the ascending node. The number of satellites in the orbit and the mean anomaly of a single satellite determine the mean anomalies of all satellites in the orbit. The satellite type assigned to a constellation can either be predefined or can be left as a variable. Furthermore, each constellation has an inclusion variable that determines whether it is actually used in the evaluation of a candidate solution. The inclusion variable permits the removal of constellations of satellite types that are deemed unnecessary during the optimization and of redundant orbits.

Launch vehicles. Launch vehicles contain parameters of existing or predicted vehicles available for the desired mission. The capacity and cost of the launch vehicle impact the optimization, especially in missions where the satellites have costs less than or equal to a launch vehicle.

Missions

The constellation ”missions” provide metrics that the optimizer seeks to maximize or minimize. For many satellite missions, it is necessary to maximize coverage over a particular region. In almost any endeavor, it is beneficial to minimize cost. In the future, other types of missions will be added as necessary. The total cost value J of a constellation is calculated as

$$J = \sum_{i=1}^{n} c_i b_i \tag{1}$$

where b_i is the cost value for mission i and c_i is the weight of mission i.

Coverage. A coverage mission is first defined by its region. The region can be global or an area bounded by a defined latitude and longitude. The coverage region is then represented as a finite number of locations spaced evenly in latitude an longitude based on a defined grid spacing. Next, the user defines which constellations, satellites, or sensors are needed for coverage and what level of multiple coverage is required. The user also defines a minimum elevation above which the ground locations are able to access the satellites. A grid point is considered to be covered by a satellite if the elevation angle of the satellite with respect to the ground at that grid point is greater than or equal to the minimum elevation angle. The coverage provided by the constellation is quantified as the average of the maximum revisit times at each grid point. In the case of a navigation constellation, the additional metric of positional dilution of precision can be used. A maximum acceptable revisit time is assigned, and a constellation that does not meet that maximum is penalized. A normalized revisit time and dilution of precision if appropriate is used as the mission cost value.

Cost. Satellite cost models are the results of statistical analysis of historical data. Therefore, the cost estimations generated using these models are only likely to be accurate if similar satellites have been manufactured before. Furthermore, cost models often base costs on the mass of individual components or subsystems. Because the constellation optimization tool is designed to be used in hypothetical situations and early in the design process in addition to being used with complete satellite designs, it is often difficult to obtain subsystem mass elements as required by most cost models.

To approximate the mass of a satellite with no capabilities beyond communications and data transfer, the transmission power is used as the determining factor. Typically, high-power amplifiers have efficiencies between 50 and 65 percent and comprise the bulk of the communications power budget.[14] The power used by the communications payload is therefore approximated as twice the transmitted to account for the inefficiency in the amplifier. A relationship between the communications payload power and the spacecraft mass was developed using statistical analysis of nongeosynchronous communications satellites at the Massachusetts Institute of Technology by Springmann and Weck. The relationship is

$$M_{dry} = 7.5 P_{PL}^{0.65} \tag{2}$$

where P_{PL} is the payload power in watts and M_{dry} is the spacecraft dry mass in kg. The same work also shows that the payload mass M_{PL} is approximately $M_{PL} = 0.27 * M_{dry}$.[15] Now that the spacecraft and payload masses have been estimated, the Unmanned Space Vehicle Cost Model (USCM8) is used to calculate the development and first flight unit costs. The total cost for N satellites is $T = T_1 * N^{1+ln(0.95)/ln(2)}$, where T is the total satellite cost and T_1 is the cost of the first flight unit.[14]

The launch vehicle costs and mass capacities were gathered from historical sources for existing vehicles and from predicted costs for future vehicles. The orbital cost function was used to approximate the mass capacity for a launch vehicle going to an arbitrary orbit based on the mass capacity of a launch vehicle going to a 185 km altitude Earth orbit.[14] The number of launch vehicles needed was approximated by calculating the number of satellites that a single launch vehicle could hold and comparing that number to the number of satellites per plane in a constellation. If there were more satellites per plane than the launch vehicle could, additional launch vehicles were required. If there were fewer satellites per plane, calculations were done to see if the launch vehicle could carry an additional plane's worth of satellites with enough propellant to transfer them to the appropriate plane. Once the total number of launch vehicles was determined, the satellite and launch vehicle costs were combined to obtain the total cost. A normalized total cost is used as the mission cost value.

Constraints

Several types of constraints have been implemented to ensure that the solution found by the optimizer is realistic. The constraints check the feasibility of the solution based on the satellite and constellation parameters alone, without propagating the satellite positions forward in time as is done with a mission. Currently implemented constraint types are link budgets, multistage link budgets, communications channel checks, and field of view checks.

Link budget. A link budget calculation to the ground can be done for any satellite. The link is assigned a data rate and a maximum allowable bit error rate. Both an uplink and downlink budget are calculated based on satellite and ground station parameters. If the resulting bit error rate is less than the allowable bit error rate, the constraint is satisfied.

Multistage link budgets. A series of transmitter-receiver relationships are defined to evaluate a signal that passes through multiple satellites or ground stations. A sensor, ground station, satellite, or constellation can be designated as a transmitter or receiver. If a sensor is chosen, any satellite or ground station containing that sensor is considered a valid candidate for the link. When multiple options are available for the transmitter or receiver, the option that gives the shortest distance between the two assets is selected. It is also required that a transmitter is on the same body as the receiver of the previous step. A data rate and maximum bit error rate are defined by the user. Because the bit error rate is the probability that an error will occur, the probability of an error-free transmission, one minus the bit error rate, is multiplied at each step. If the total bit error rate, one minus the total probability of an error-free transmission, is less than the maximum allowable bit error rate, the link is sufficient. Furthermore, multiple alternate link paths can be designated that allow the constraint to be satisfied if any one of several multistage paths gives a satisfactory link.

Communications channel check. If a constellation or satellite is accessed by many users simultaneously, the satellite must have a sufficient number of channels to accommodate all users. Currently, all satellites are assumed to use frequency division multiple access techniques, though future iterations of the software will add additional multiple access schemes. A rough calculation of the number of required channels per satellite is done by multiplying the number of simultaneous users by a factor approximating the average number of cross links per communication and dividing by the number of available satellites. The average number of cross links increases as the ground area covered by a single satellite decreases. If the satellite has a number of communications channels greater than or equal to the required number, the constraint is satisfied.

Field of view check. For a nadir-pointing satellite that communicates only with locations on the ground, a field of view that extends beyond the surface of the planet wastes energy. To assist the simulation in more rapidly converging upon an optimal solution, a satellite's field of view can be limited to the surface of the planet.

Optimizer

A genetic algorithm solver is used to find a near-optimal solution to the missions defined by the user, subject to the imposed constraints. The genetic algorithm starts with a set of candidate solutions. Each candidate solution is represented by a genome, a string of numbers corresponding to all of the variables describing the characteristics of the assets, as well as an inclusion variable on each constellation. The algorithm steps through evaluation, crossbreeding, mutation, and constraint

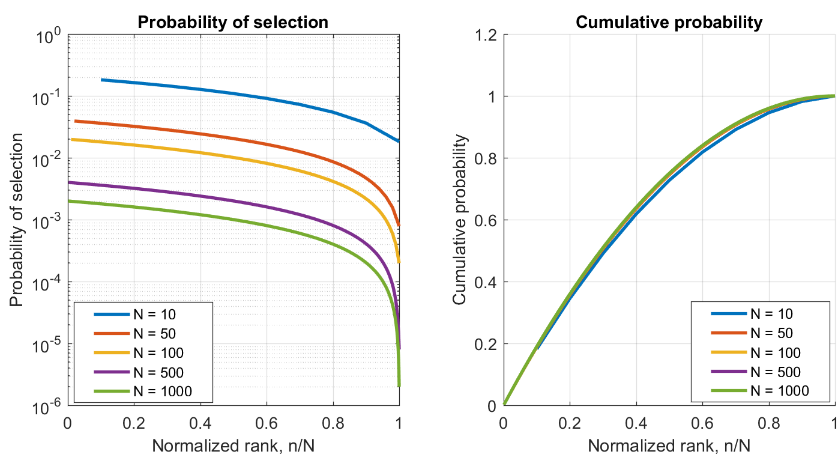

Figure 2. Odds for mating selection

checking. In the evaluation step, the fitness value of each candidate solution is calculated based on its ability to fulfill the mission requirements. Solutions are then ranked from the lowest, best cost value to the highest. A designated percentage of the most fit individuals is retained for the next generation. The remainder of the next generation is created by "mating" a designated percentage of the most fit individuals from the current generation. For example, if the generation has 100 population members, one could decide to keep the best six and breed the next generation from the top 40. Because 94 population members are required in addition to the top six, 94 children must be produced from 47 matings.

The parents for each mating are selected from the potential pool of parents using odds that are weighted in favor of more fit individuals. The odds of the n-th most fit candidate being selected for parenthood out of N potential parents are[16]

$$P_n = \frac{N-n+1}{\sum_{i=1}^{N} i} = \frac{2(N-n+1)}{N(N+1)} \tag{3}$$

Figure 2 shows the odds of selection for each individual of populations of various sizes. It also shows the odds that the selected candidate will be in $[1, n]$.

Once the parents P_1 and P_2 are chosen, the mating is performed. Two elements of P_1 are randomly chosen to be the starting and ending points of the segment to be crossed over. In a scenario with a fixed number of satellites, a weighted average of random weight is performed with the same segment of P_2. However, the optimizer also permits cases in which the number of constellations can vary. Variable genome length is particularly useful for missions requiring irregular coverage zones that would not benefit from a traditional Walker constellation. A probability that a length change will occur, ϵ, is chosen. If a random number r from zero to one is less than the length change probability, two elements of P_2 are chosen as separate starting and ending points. If the number of elements in the crossover segment of P_1 differs from that of P_2, the resulting children will have different lengths than the parents. However, when performing a crossover of this kind, only similar elements may be swapped. A check is in place to guarantee that the starting and ending points of P_1 and P_2 are of the same type.

Once mating operations have been performed the appropriate number of times to fill the next generation, the generation undergoes mutation. A set mutation rate is declared. The number of variables to be mutated is equal to the mutation rate times the total number of elements contained in all of the population members except the first, most fit member. The positions of the mutations are then chosen at random from variables across all members except the first, and the mutating elements are randomly set to some value within the possible set of values for that element. After all mutations have been performed, the next generation is defined.

However, the candidate solutions must be checked against the constraints prior to moving on to the evaluation step. The constraints can be linear or nonlinear and are of the forms

$$\begin{aligned} Ax &\leq b \\ A_{eq}x &= b_{eq} \\ c(x) &\leq 0 \\ c_{eq}(x) &= 0 \end{aligned}$$

where x is the genome representing a solution, A and A_{eq} are matrices describing the linear constraints along with the vectors b and b_{eq}, and c and c_{eq} are vector functions describing the nonlinear constraints. The genome is checked against each constraint in turn. If a constraint is violated, a component of the genome affecting that constraint is randomly selected and mutated. The elements affecting a linear constraint are the elements corresponding to a nonzero element in the row of the A or A_{eq} representing that constraint. The elements affecting a nonlinear constraint must be provided by a separate function defined in conjunction with the constraint. In the case of an element with a small number of possible values, such as a binary value, the new element is required to be different than the original element. The new element is inserted into the genome and all of the constraints are rechecked. This process continues until all constraints are satisfied for a single genome, then repeats for every candidate solution. The corrected next generation is evaluated for fitness and the entire process repeated until some stopping criterion is met. The current stopping criteria are a maximum allowable number of generations and a number of generations required for sufficient dominance. The latter condition is satisfied if a solution has been the best solution of the population for a number of generations defined by the user.

Propagator

Two types of propagators are currently available for use in the software. The first is a numeric fourth-order propagator. The gravitational potential field of a body can be approximated from measurements as a series of spherical harmonics,

$$V = -\frac{\mu}{r}\left(1 + \sum_{l=2}^{\infty}\left(\frac{a_e}{r}\right)^l \sum_{m=0}^{l}\left[\overline{C_{lm}}\cos(m\lambda) + \overline{S_{lm}}\sin(m\lambda)\right]\overline{P_{lm}}(\sin(\phi))\right) \tag{4}$$

where V is the gravitational potential energy per unit mass; μ is the standard gravitational parameter for the planet; r, λ, and ϕ are the radius from the planet's center to the satellite, the longitude of the satellite, and the geocentric latitude of the satellite; a_e is the reference radius of the planet used to develop the model; $\overline{C_{lm}}$ and $\overline{S_{lm}}$ are coefficients; and $\overline{P_{lm}}(\sin(\phi))$ is the normalized associated Legendre polynomial of degree l and order m, evaluated for $\sin(\phi)$.

Because of computation considerations, the series is truncated after the $l = 4$ term. The gravitational force can be found from the gravitational potential by taking the negative gradient of the potential energy, $F_g = -m\nabla V$. Since r, ϕ, and λ are spherical coordinates of the spacecraft, the spherical gradient can be used. The force is then rotated into inertial coordinates and the acceleration calculated. A fourth order Runge-Kutta integrator is used to find the spacecraft position and velocities over time.

The computation time for numerically integrating the equations of motion described in the previous parargraphs becomes prohibitive for long scenario periods. Either the task can be outsourced to supercomputing resources, or the model must be simplified. Common simplifications of gravitational effects due to spherical harmonics are the J_2, J_4, and J_6 formulations.[17,18] These derivations consider only the zonal harmonics up to six. They also neglect periodic terms, considering only secular terms in the potential formulation. They then use the Lagrange variation of parameters equations with the reduced potential. The result is a formulation in which the semimajor axis a, eccentricity e, and inclination i are treated as constant or as having short- and long-term periodic motion. The rate of changes of the longitude of the ascending node, Ω, the argument of periapsis,

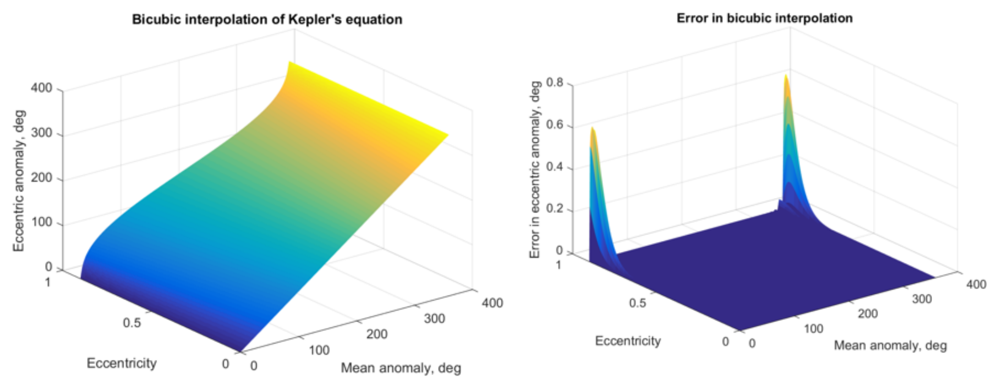

Figure 3. Bicubic interpolation of Kepler's equation and error of interpolation

ω, and the mean anomaly, M, due to the second and fourth order terms are

$$\begin{aligned}
\dot{\Omega}_{sec} &= -\frac{3J_2a_e^2n\cos(i)}{2p^2} + \frac{3J_2^2a_e^4n\cos(i)}{32p^4}\Big(12-4e^2-(80+5e^2)\sin^2(i)\Big) \\
&+ \frac{15J_4a_e^4n\cos(i)}{32p^4}\Big(8+12e^2-(14+21e^2)\sin^2(i)\Big) \\
\dot{\omega}_{sec} &= \frac{3nJ_2a_e^2}{4p^2}\Big(4-5\sin^2(i)\Big) + \frac{9nJ_2^2a_e^4}{384p^4}\Big(56e^2+(760-36e^2)\sin^2(i)-(890+45e^2)\sin^4(i)\Big) \\
&- \frac{15J_4a_e^4n}{128p^4}\Big(64+72e^2-(248+252e^2)\sin^2(i)+(196+189e^2)\sin^4(i)\Big) \\
\dot{M} &= n + \frac{3na_e^2J_2\sqrt{1-e^2}}{4p^2}\Big(2-3\sin^2(i)\Big) \\
&+ \frac{3na_e^4J_2^2}{512p^4\sqrt{1-e^2}}\Big(320e^2-280e^4+(1600-1568e^2+328e^4)\sin^2(i)+(-2096+1072e^2+79e^4)\sin^4(i)\Big) \\
&- \frac{45J_4a_e^4e^2n\sqrt{1-e^2}}{128p^4}\Big(-8+40\sin(i)-35\sin^2(i)\Big)
\end{aligned}$$

where $p = \frac{h^2}{\mu} = a(1-e^2)$ is the semi-parameter, n is the mean motion, and the J_2 and J_4 constants are the negatives of the second and fourth order non-normalized zonal harmonic coefficients. These rates of change are treated as constant, so the parameters at time t can be found by mutliplying the rates of change by t and adding these values to the parameter values at $t = 0$. Once mean anomaly is known, the true anomaly ν can be calculated via the eccentric anomaly E and Kepler's equation. Kepler's equation, $E - e\sin(E) - M = 0$, is transcendental in E and so must be solve numerically. A bicubic interpolation was developed that approximates E as a function of M and e. The interpolation surface is shown in Figure 3, along with its error compared to solving Kepler's equation by bisection with an allowable approximate relative error of 10^{-12}. The true anomaly is then calculated from the eccentric anomaly through the relationship $\tan\frac{\nu}{2} = \sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2}$. Once the true anomaly is known, the satellite position and velocity can be calculated from the classical orbital elements. This method reduces computation time by ninety percent while maintaining the dominant gravitational perturbations and is therefore applicable for orbits around central bodies whose perturbations are dominated by second and fourth order effects and who experience little perturbation due to air drag or third body effects.

SCENARIO

To support an early human settlement on Mars, it is necessary to establish communications and navigation infrastructure. Due to the difficulty of transporting equipment to the planet's surface, it is likely that much of Mars' infrastructure will be space-based. Optimization was performed to find a constellation that could: 1) provide voice communications for 5000 simultaneous users, 2) provide position, navigation, and timing (PNT) capabilities globally, and 3) enable data transmission back to Earth with speeds of 1 Mbps. The ability to provide voice communications was quantified using a globally averaged maximum revisit time and a channel capacity constraint. Each voice transmission required a data rate of 9.6 kbps and a maximum bit error rate of 10^{-3}, which are standard requirements for satellite voice communications used by constellations such as Globalstar.[19] The ground segment of the communications link was modeled after current tactical radios, with a transmit power of 3.2 W and a gain of 1 dB. The PNT requirement was considered to be satisfied if points on a defined grid across the globe had continuous coverage from at least four satellites with a data rate of 50 bps and a maximum bit error rate of 10^{-5}. It is assumed that the positioning satellites will have sufficient knowledge of their own positions from established ground stations or transmitters. The data transmission requirement was checked by examining the multistage link budget connecting a theoretical Mars high-powered ground station to the Deep Space Network on Earth in the worst case scenario when Mars and Earth are separated by 2.5 AU. transmitting a signal at 8 GHz and 100 W with an antenna half angle of 0.18 deg. The frequency and gain parameters of the ground station were set to match those of the Mars Reconnaissance Orbiter.[20] The half angle of satellite-based transmitters and receivers involved in the data transfer was also defined as 0.18 deg, though the power was set as a variable to be determined during the optimization. The maximum acceptable bit error rate was set at 10^{-7}.

Four potential satellite types were identified. The first type, NAVIGATION, was a PNT only satellite that transmitted at the low data rate of 50 bps. The second type, COMMS, was a communications satellite that had a variable number of channels available to permit multiple access. It was presumed that COMMS could transmit the necessary PNT signal with no additional equipment or power due to the low data rate. Also, COMMS could be assigned a deep space transmitter and receiver, though it was not required. Both NAVIGATION and COMMS were assigned to Walker Delta constellations. The third type, MARS RELAY, was a Mars-orbiting satellite hosting a deep space transmitter whose sole function was to transmit data to Earth or to a second relay constellation. It was assigned to a near-equatorial circular plane. A fourth type, SUN RELAY, was added to consider the possibility of having lower-powered Mars-orbiting satellites transmit to relatively near Sun-orbiting satellites that could then transmit to one another to reach a satellite near Earth.

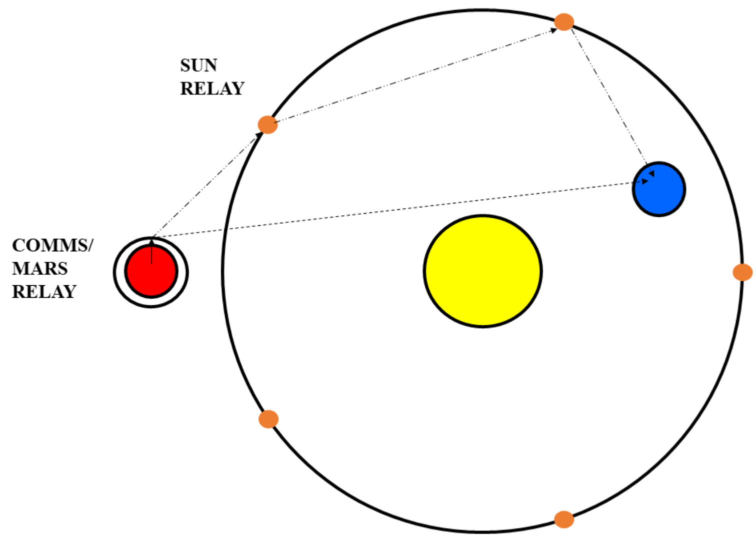

Figure 4. Potential data relay paths.

Table 1. Constellation properties

Properties	NAVIGATION	COMMS	MARS RELAY	SUN RELAY
Transmit Frequency (GHz)	[0.2, 0.4, 1.5, 2.5, 5.9, 7.9]	[0.2, 0.4, 1.5, 2.5, 5.9, 7.9]	8.0	8.0
Transmit Power (W)	0.1-50	0.1-1000	10-500	10-500
Antenna Half Angle (deg)	5-90	5-90	0.18	0.18
Number of channels	1	1-1000	1	1
Semimajor axis (km)	3596-21396	3596-21396	3596-21396	$(1.496 - 2.274) * 10^8$
Inclination (deg)	2-90	2-90	2	0
Satellites per plane	1-20	1-20	1-20	1-10
Number of planes	1-20	1-20	1	1
Central body	Mars	Mars	Mars	Sun
Additional sensors	-	Deep space transmitter (10-500 W)/ receiver (optional)	-	-

An illustration of the potential transmission paths is shown in Figure 4. The range of spacecraft and orbit parameters is shown in Table 1.

The simulation was run using the the bicubic interpolation J4 propagator described in the previous section. The simulation time period was initially set for ten days, but is checked over a longer period of time once the simulation is complete if the final solution contains satellites at different inclinations that would be subject to different perturbations. Potential launch vehicles were determined from previous and planned Mars missions and include the Polar Satellite Launch Vehicle (PSLV), the Space Launch System, and the Atlas V 541. The genetic algorithm used a mutation rate of 0.05 and a population size of 300. The top one percent of candidates were kept for the next generation, with the best candidate remaining unmutated. The top seventy percente were considered as potential parents. The optimization was permitted to run for up to 600 generations, with fifty generations of unchanged dominance considered sufficient to conclude the optimization.

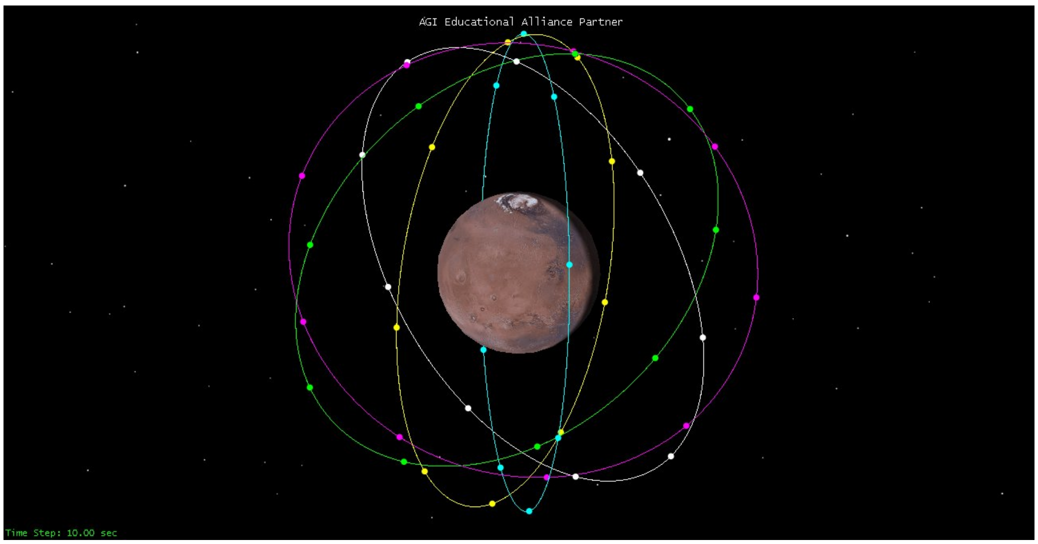

Figure 5. STK visualization of final constellation.

Table 2. Constellation properties

Properties	Value
Comms frequency (GHz)	0.2
Comms transmit power (W)	6.5
Comms half angle (deg)	23.7
Comms number of channels	173
Semimajor axis (km)	9818
Inclination (deg)	85.2
Satellites per plane	9
Number of planes	5
Walker phasing parameter	1
Deep space transmit power (W)	29.3

RESULTS

The simulation determined that the most cost effective solution was to use a single type of satellite, a communications satellite augmented with an additional deep space transmitter and receiver. The resulting satellite and constellation had the parameters shown in Table 2. STK was used to create a visualization of the constellation, which is shown in Figure 5. The satellite will have a mass of approximately 120 kg. The estimated costs for the constellation, in 2010 dollars, are $1.3 billion for development, $27 million for the first flight unit, $900 million for all satellites, and $225 million for fifteen PSLVs, giving a total mission cost of $2.5 billion.

The constellation provides continuous four-fold coverage over the entire planet. The maximum geometric dilution of precision of the constellation was calculated using Systems Tool Kit (STK) and ranged between 1.2 and 2.1 for various latitudes. The voice communications have an uplink bit error rate of $6.9 * 10^{-5}$ and a downlink bit error rate of $7.7 * 10^{-4}$. The bit error rate for the PNT data is insignificant due to the low data rate. The bit error rate for data transmission to Earth is $8.3 * 10^{-8}$.

The constellation tool performed as expected, with the optimization undergoing 239 generations before fifty generations of continuous dominance was achieved. Ultimately, a single satellite type was the most viable likely due to development and launch costs, which could have eliminated the two relay satellite types. The number of communications satellites needed made the additional PNT satellites unnecessary. If a satellite were made with commercial off-the-shelf components and the cost modeled accordingly, it is possible that a multiple satellite solution would become preferable. Furthermore, if the target area of the communications constellation were reduced to the equatorial region, it is likely that the lower cost PNT satellites would be a superior choice to provide the remaining coverage. To ensure that additional satellite types were not prematurely excluded, additional runs can be performed both of the same simulation and of simulations that force the inclusion of additional satellite types.

CONCLUSION

The software developed during this research effort was able to successfully design a constellation of Mars-orbiting satellites that met mission requirements for voice communications, data relay, and PNT. Although both heterogeneous and homogeneous constellation types were considered, it was determined that the best solution was a highly inclined Walker Delta constellation of five planes with nine satellites per plane. The satellites transmit at 0.2 GHz for voice communications using frequency division multiple access techniques and at 8 GHz for data transfer to Earth. Although the resulting constellation was not heterogeneous, the Mars scenario showed that the research done is useful for comparing both traditional single-satellite constellations and disaggregated multiple-satellite constellations.

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REFERENCES

[1] R. E. Thompson, *A Methodology for the Optimization of Disaggregated Space System Conceptual Designs*. PhD thesis, Air Force Institute of Technology, 2015.

[2] R. E. Thompson, J. M. Colombi, J. Black, and B. J. Ayres, "Model-Based Conceptual Design Optimization Methods: Disaggregated Weather System Follow-On," *Journal of Spacecraft and Rockets*, Vol. 52, No. 4, 2015, pp. 1021–1037.

[3] J. M. Colombi, L. D. Buckle, J. T. Black, and S. G. Nurre, "Optimal Launch Manifesting for Heterogeneous Disaggregated Satellite Constellations," *Journal of Spacecraft and Rockets*, Vol. 54, 2017.

[4] R. E. Thompson, J. M. Colombi, J. Black, and B. J. Ayres, "Model-Based Conceptual Design of Disaggregated Space System Architectures," *Systems Engineering*, Vol. 18, No. 6, 2015.

[5] J. F. Lam, P. L. Tour, , and J. Kim, "Architecting Disaggregated Space Weather Solutions using Nanosatellites," *AIAA SPACE 2013 Conference and Exposition*, 2013.

[6] e. a. Billy E. Johnson, "U.S. Army Small Space Update," *Proceedings of the AIAA/USU Conference on Small Satellites*, 2016.

[7] M. F. e. al, "Efficient and accurate evolutionary multi-objective optimization paradigms for satellite constellation design," *Journal of Spacecraft and Rockets*, Vol. 44, 2007, pp. 682–691.

[8] C. Y. Lee and E. K. Antonsson, "Variable Length Genomes for Evolutionary Algorithms," *Genetic and Evolutionary Computation Conference*, 2000.

[9] B. G. C. e. al, *Practical Handbook Of Genetic Algorithms: Applications*, ch. How to handle constraints with evolutionary algorithms., pp. 341–361. CRC Press, 2001.

[10] W. H. Gerstenmaier, "Progress in Defining the Deep Space Gateway and Transport Plan," Briefing, March 2017.

[11] SpaceX, "Mars Talk," SpaceX website, April 2017.

[12] T. Ely *et al.*, "Mars Network Constellation Design Drivers and Strategies," *AAS/AIAA Astrodynamics Specialist Conference*, 1999.

[13] I. Nann *et al.*, "A Reconfigurable Mars Constellation for Radio Occultation Measurements and Navigation," *4th International Workshop on Satellite Constellation and Formation Flying*, 2005.

[14] D. F. E. James R. Wertz and J. J. Puschell, eds., *Space Mission Engineering: The New SMAD*, pp. 298–299, 316, 486. Microcosm Press, 2015.

[15] P. N. Springmann and O. L. d. Weck, "Parametric Scaling Model for Nongeosynchronous Communications Satellites," *Journal of Spacecraft and Rockets*, Vol. 41, No. 3, 2004.

[16] R. L. Haupt and S. E. Haupt, *Practical Genetic Algorithms*. Wiley and Sons, 2004.

[17] D. A. Vallado, *Fundamentals of Astrodynamics and Applications, 4th ed.*, ch. General Perturbation Techniques, pp. 609–654. Microcosm Press, 2013.

[18] R. H. Merson, "The Motion of a Satellite in an Axi-Symmetric Gravitation Field," *Geophysical Journal of the Royal Astronomical Society*, Vol. 4, No. 17, 1961.

[19] W. J. Larson and J. R. Wertz, eds., *Space Mission Analysis and Design*, ch. Communications Architecture, pp. 533–586. Microcosm Press and Kluwer Academic Publishers, third ed., 1999.

[20] J. Taylor, ed., *Deep Space Communications*, ch. Mars Reconnaissance Orbiter, pp. 201–259. John Wiley and Sons, Inc., 2016.