The Flower Constellations Visualization and Analysis Tool

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Abstract—The Flower Constellations is a novel methodology to design satellite constellations characterized by compatible orbits with respect to an assigned given rotating reference frame. In this rotating reference frame all the satellites follow the same close-loop relative trajectory (repeated space tracks). A Flower Constellation is obtained by means of a suitable phasing mechanism that initially distribute the satellites in a subset of admissible positions. The interplay of the design parameters generates beautiful and intriguing axial-symmetric periodic dynamics. These dynamics allow us to explore a wide range of potential applications which include: telecommunications, deep space observation, global positioning systems, and allows us to quickly come up with highly complex satellite formations that no one even knew existed and, consequently, to propose new kind of space missions. These constellation schemes are dramatically innovative and could be hardly imagined, designed or explained without the aid of an ad-hoc visualization software. In this paper we describe the software we developed to design the Flower Constellations with its current features and future improvements.

INTRODUCTION

The design of artificial satellite constellations is gaining importance both for classical applications, such as telecommunications and global navigation (GPS or GPS-like), and for the more innovative concepts of very large aperture interferometry in space (SAR and InSAR systems). It is expected that the next generation of satellites will feature more cooperation of smaller, redundant, and less expensive spacecrafts. The cooperation of a number of spacecrafts can be accomplished using formation flying or constellation schemes. The real difference between the two concepts of formation flying and constellation is actually unclear. However, the terminology commonly used identifies a constellation when the inter-satellite distances are very great (higher than a few kilometers), while formation flying identifies much shorter inter-satellite distances (lower than a few kilometers). We have adopted the name of “Flower Constellations” (FCs) because - theoretically - there is no upper limit to the inter-satellite distances.

A literature research on the constellation subject reveals that constellations have been used in order to assure coverage of an area on the ground for communications (COBRA [5], LOOPUS [4]), for global navigation (GPS [15], [8], [7], [10], Galileo [10], [6]), and for surveillance (i.e. Molnya Orbits). During the last two decades a number of new constellation concepts, similar in nature, have been developed. Mainly these constellations are built upon a subset of the existing many categories of satellite orbits: Low Earth Orbits (LEO), Molniya (a subset of Highly Eccentric Orbits - HEO), TUNDRA orbits, Geosynchronous/Geostationary Earth Orbits (GEO). However, up to now, no general theory of constellations exists that helps the engineers in achieving the desired coverage or to satisfy a different specific mission target. Due to the inherent complexity of the general constellation design, the Walker constellations [17], [18], which use circular orbits, became so popular and are the most common type encountered in practice, while HEO based constellations are rarely used.

The theory of Flower Constellations poses no constraint in the kind of orbits to be used. The Flower Constellations can be made using circular or elliptical orbits, and equatorial or inclined orbits. The resulting dynamics present interesting features that the Flower Constellations Visualization and Analysis Tool (FCVAT) greatly help to exploit. These FCs are of interest in the telecommunications industries for their ability to address global and regional telecommunications coverage in those areas where there is poor reception from GEO satellites (i.e. Northern Europe) [9].

Mortari et al. [14], [20], [21], have introduced the Flower Constellations as a general theory for the design of very wide class of constellations. It has been also proved that many of the previous constellations, including but not limited to the GPS and Galileo, can be easily reproduced as Flower Constellations.

Such a novel design methodology requires visualization capabilities and ad hoc interaction with the designer that is not present in the available commercial products, of which the most widely used is Satellite Toolkit (STK) by Analytical Graphics Inc. (AGI). It is for this reason that a new software, the Flower Constellation Visualization and Analysis tool (FCVAT), has been developed and modified in a tight development loop to include the latest discoveries from the theoretical work.

This paper will briefly refresh the basic theory of Flower Constellations and then describe the features of the current version of the software. In the last part of the paper the new features that would be desirable to add will be described and in the conclusion the highlights will be summarized.
Wilkins in [19] describes the *Flower Constellations* as

A method that can be used to design constellations of satellites and formation flying schemes. FCs are characterized by an axis of symmetry that can be arbitrarily oriented. When the FC axis of symmetry is aligned with the Earth spin axis, then the satellites will have identical repeating ground tracks.

Also, quoting from [19] to the reader’s benefit:

*Flower Constellations* are identified by eight parameters. Five are integer parameters: the number of petals ($N_p$), the number of sidereal days to repeat the ground track ($N_d$), the number of satellites ($N_s$), two integers to rule the phasing ($F_n$ and $F_d$), and three orbit parameters that equal for all satellites: the argument of perigee ($\omega$), the orbit inclination ($i$), and the perigee altitude ($h_p$). Each of these parameters has a unique effect on the overall design of a FC. Specific choices of these parameters will produce certain effects. Inverse design techniques can also be used: the integer parameters are solved for to achieve a desired final constellation or formation shape. Often, a large number of satellites are used to completely visualize these constellations. Thus, *Flower Constellations* lend themselves to micro- and nano-satellite constellations very easily. However, *Flower Constellations* are readily scalable to any mission requirement.

The original design and motivation for FCs was the desire to describe with few parameters the class of constellations that have a repeating ground track. The latter is a desirable property for the purpose of satellite tracking since there is, discarding the perturbations of the orbits, no need to change the pointing of the antenna in the ground station. Subsequently, the theory has been refined, achieving a better understanding of the problem and the repeating ground track concept has been generalized to become compatible orbits[3] when an arbitrary rotating reference frame is introduced.

The problem with satellite constellation or formation flight near a planet is the difficulty and high cost of formation keeping. This is due to the inherent instability of satellites in nearby Keplerian orbits of slightly different periods or phase. Therefore, designing formations near planets has been very challenging. The discovery of “natural formations” where no control is required to achieve a desired configuration is therefore desirable.

Thus, they hold great promise for many potential applications both at Earth and around other planets. These orbits are similar to orbits with repeating ground tracks which have proved so useful for orbiter missions in the past. *Flower Constellations* have “repeating space tracks” with clusters of satellites. They can be used to study the space environment around planets and moons using satellite formations with very little fuel and low operations cost.

![Figure 1](Image)

**Figure 1.** The trajectory of the satellites as seen from the ECEF frame

In order to explain the FCs at least two reference frames are introduced: the Earth Centered Inertial (ECI) frame (with the origin at the center of the Earth, the $x$ axis pointing to the Vernal Equinox, and the $z$ axis aligned with the North pole) and the Earth-Centered, Earth-Fixed (ECEF) frame (where the $x$ axis is the vector from the Earth’s center to the intersection of the Greenwich meridian and the equator). As it is well known, in the ECI frame the satellite trajectories, within the two body problem approximation, are ellipses with the Earth in one focus. On the other hand, if we describe the spacecraft trajectory in the ECEF frame (or, more generally, any rotating frame) the trajectories appear as intriguing closed paths that, in general, can not be described with a simple geometry. An example of this can be seen in Fig. 1. The ECEF trajectory is usually referred to as relative path and have also been described as “repeating space tracks”. Since the position vector is the same in all the reference frames, the satellites center of mass always belong to an intersection point between the inertial and relative trajectory.

All the orbits of the satellites in a flower constellation have the same shape, and there could be more than one satellite that share the same inertial orbit. The only orbital elements that vary from one satellite to another are, in general, the Right Ascension of Ascending Node (RAAN) usually written as $\Omega$ and the Mean anomaly at time $M(t_0)$. The constraint that is always enforced in a FC is that all the satellite share the same relative path, calculated with respect to some relative frame (i.e. ECEF). The relations used to distribute the RAAN and $M(t_0)$ are as follows:

$$\Omega_{k+1} = \Omega_k - 2\pi f(F_n, F_d)$$  \hspace{1cm} (1)

$$M_{k+1}(t_0) = M_k(t_0) + 2\pi f(F_n, F_d) \left( n + \frac{M_0}{\omega_{\oplus} + \Omega} \right)$$  \hspace{1cm} (2)
In order to achieve this wholistic approach in the constellation the single satellite. the design parameters, and do not concentrate the attention on completely different constellation. Coprime numbers in the changing one of the integer parameters can result in a com-

existing software fully satisfied these requirements, therefore relative path from the ECI to the ECEF frame. None of the change the reference frame used for the visualization of the relative path. With an opportune choice of the inclination (i.e. i = 63.4 deg, for a prograde orbit) it is possible to reduce the effect of the perturbations to a simple precession of the lines of nodes.

A full explanation of the FC theory is beyond the scope of this paper and the interested reader is invited to see the papers in the reference or to visit the web site http://flowerconstellations.tamu.edu.

THE FCVAT SOFTWARE

Since the beginning of the development of the FC theory the goal was to design the constellation as a whole “object”, using the design parameters, and do not concentrate the attention on the single satellite.

In order to achieve this wholistic approach in the constellation design there was the need of an user interface that supported such vision. It was also needed a tool that allowed to quickly change the reference frame used for the visualization of the relative path from the ECI to the ECEF frame. None of the existing software fully satisfied these requirements, therefore the development of the FCVAT started. The development of the software and of the theory so far have proceeded in parallel, with continuous mutual feedback.

The interplay between the parameters, although governed by simple relations, produces results that are very difficult to imagine or foresee without a visualization tool. Simply changing one of the integer parameters can result in a completely different constellation. Coprime numbers in the $F_n$, $F_d$ parameters result in the most interesting dynamics and, for particular choices, the dynamic interplay of the satellites produces relative motions (relative to the other spacecrafts) whose dynamics are synchronized to a new reference system that is neither the ECI nor the ECEF. The satellites distribution, in this case, generate new dynamical paths that have been called “secondary paths”.

A secondary path is generated when a mathematical property is satisfied among the input integer parameters. During the construction of a FC, on $F_d$ evenly distributed orbits a maximum of $F_d \times N_q$ satellites can be allocated. However, for some specific values of the input parameters not all the $F_d \times N_q$ available slots are occupied and therefore the initial distribution of satellites does not constitute a closed loop.

The full effect of secular terms of the perturbations due to various sources is still being investigated, but in [13] Mortari et al. introduced the effect of the Earth Oblateness ($J_2$ coefficient) on the FCs. The Earth’s oblateness causes a variation of the orbital elements that in turn changes the shape of the relative path. With an opportune choice of the inclination (i.e. $i = 63.4$ deg, for a prograde orbit) it is possible to reduce the effect of the perturbations to a simple precession of the lines of nodes.

When this happens the FC produces a secondary path. Figures of secondary path can not be produced, since these dynamics becomes clear only through animation of the spacecraft motions. The interested reader is invited to visit the web site to download the animation files and observe these dynamics. An attempt to show some frames from such animation is shown in the figures from 4(a) to 4(d).

The FCVAT, whose main window is shown in Fig. 2 has been written entirely in Java, using the Java3D extensions for the 3D visualization and the SWING libraries for the Graphical User Interface (GUI). With this choice we achieved the desired application portability and abstraction from hardware. Java3D is an object oriented 3D rendering and animation engine, freely available from Sun Microsystems, built on top of OpenGL, of which shares many of the functionalities, but also provides higher level functions and utilities.

The FCVAT is an interactive simulation application. The user sets the parameters of the constellation through a side panel where the various parameter can be specified entering text in the appropriate boxes (see Fig. 3). The parameters are grouped according to their function in a specific tab.

Since in a constellation all the satellites share the orbital parameters there is no need to specify the orbital elements for all the satellites. The distribution of the satellites along the relative path is accomplished using various phasing schemes, which phasing scheme is chosen has a great impact on the kind of formation flying or constellation that can be achieved. The full possibilities of the FC and how to solve the inverse problem (given the mission requirements find the optimal flower constellation to satisfy them) is still being researched. Some initial results have been provided by Wilkins et al. in [20].
The FCVAT has been designed so that it is very easy to switch the reference frame to which the viewpoint is attached. For instance, if the ECEF frame is chosen then the user will observe that the inertial orbits appear to be rotating about the Earth, while if the ECI is chosen, then it will be the relative path to appear as rotating.

The animation can be paused and resumed. The viewer can orbit the scene to observe it from a different vantage point during the animation. Usual zooming in/out and pan movement are also available. The constellation design can be saved to a file and exported in ascii format, easily readable by MATLAB or other applications. In Fig. 4 a sequence of frames from an interesting constellation \((N_p = 13, N_d = 5, N_s = 72, F_n = 14, F_d = 72)\) has been included. The unusual pattern of frame 1 is transformed into a set of 5 satellite rings and then the pattern transform back into the original one, repeating this cycle.

The constellation designer can add more FCs to the scene, thus combining the characteristics of more than just one constellation to achieve his/her goals. Using this combination of characteristics it is possible to build constellations with hundreds of satellites and see convoluted formation flying schemes within minutes.

As an example, the JOCOS constellation \([16]\) can be easily seen as the combination of two identical flower constellations (with three petals, and the only difference being the inclination). Similarly, the recently proposed Galileo constellation can be reproduced by three flower constellations with three different inclination planes. A general method to build constellations that can meet specific design constraints and maintain the desired formation scheme, is still being investigated.
One approach, investigated by Wilkins, is to project the desired shape onto the “orbital surface” generated taking the surface generated by a $2\pi$ revolution of the inertial orbit of one satellite about the z axis, and finding the FC that intersect all the satellites in admissible locations.

Other applications of the FCs are being sought in the reconnaissance problem [1], and in novel orbital concepts like the Two Way Orbits (to be published) [11], for planetary exploration [12], and Earth Observation [2]. For the reconnaissance problem, genetic algorithms have been applied to find the FC that can visit an arbitrary number and location of sites within a specified time span. A wider class of problems where the FC are promising is the synthetic aperture radar and very large baseline interferometry in space. These problems are being investigated through a collaboration with JPL.

Since the FC is a general concept, it is not limited to orbit the Earth: the FCVAT allows one to design constellations around any planet in the Solar System and even to design different bodies with the desired characteristics. It is easy to design a flower constellation about Mars or any other planet in the Solar System. The ability to freely choose the orientation of the symmetry axis, together with the possibility of choosing the angular velocity of the associated frame, allows a greater flexibility than just repeating ground track.

**CONCLUSION**

*Flower Constellations* are a recently introduced (2002) general set of constellations characterized by a repeating closed trajectory in an arbitrary rotating reference frame.

The FCVAT software represents a novel approach to constellation design and has been of fundamental help to the recent discoveries on the properties of the Flower Constellations and particularly in revealing the interplay of the satellite motions that generates the so called secondary paths. The tool is still in its initial development phase and many more important improvements are desirable, for which more funds are being sought.

The effect of the perturbation, and specifically of the zonal harmonics of the Earth gravitational field other than $J_2$ need to be included in the model. The current FCVAT also need a better interface with the software commonly used by the aerospace researchers, like STK and MATLAB for further analysis after the initial design.

Calculation of the satellites motion need to be done as a batch process in order to include the effect of various perturbations.

Specific application of Flower Constellations for Earth Science, Deep Space observation and formation flying are being investigated by the authors.

**REFERENCES**


