Initialization of Distributed Spacecraft for Precision Formation Flying

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Abstract— **In this paper we present a solution to the formation initialization (FI) problem for N distributed spacecraft located in deep space. Our solution to the FI problem is based on a three-stage sky search procedure that reduces the FI problem for N spacecraft to the simpler problem of initializing a set of sub-formations. We demonstrate our FI algorithm in simulation using NASA's five spacecraft Terrestrial Planet Finder mission as an example.**

I. Introduction

Spacecraft formation flying has been identified as a critical technology for 21st century NASA astrophysical and Earth science missions. Specifically, formation flying refers to a set of distributed spacecraft with the ability to interact and cooperate with each other. In deep space, formation flying enables variable-baseline, interferometers that can probe the origin and structure of stars and galaxies with high precision. In addition, such interferometers will serve as essential instruments for discovering and imaging Earth-like planets orbiting other stars. Ultimately, the goal is to utilize distributed spacecraft interferometers to search for bio-signatures in the atmospheres of extra-solar planets.

In order to accomplish these scientific objectives interferometers with baselines that range from tens to tens of thousands of meters are required. The operation of such interferometers relies upon the ability of precision formation control systems to maintain relative spacecraft positions and orientations to an accuracy on the order of 1 centimeter and 1 arc minute, respectively, over large distances.

However, before precision formation coordination and control can occur, it is first necessary for spacecraft to be able to communicate and to acquire the relative positions and velocities of one another. For example, after initial spacecraft deployment or after a fault condition, the spacecraft are effectively lost-in-space in the sense that the spacecraft are not communicating and do not have knowledge of relative range, bearing, and velocity between each other. Although inertial position knowledge of each spacecraft is typically available, it cannot be used to initialize the formation as it is not known to required accuracy. As a result, each spacecraft must perform a coordinated sky search to autonomously acquire relative state information. Note that the inertial attitude of each spacecraft is typically known with high accuracy from on-board star trackers and can be utilized in FI process.

The process of using on-board sensors to establish communication among the formation members and to acquire the relative positions and velocities of a set of distributed spacecraft is known as "Formation Initialization." Since formation acquisition sensors (e.g. AFF [1]) typically have limited field of view, a search is necessary to acquire formation members; this search involves coupled translational/rotational maneuvers. As a result, the FI problem becomes a formation guidance problem involving translational/rotational path planning and collision avoidance.

Although there has been some previous work in the area of deep space guidance [2], [3], [4], [5], [6], the area of formation initialization is significantly underdeveloped. The work of Breckenridge and Ahmed [7] at JPL focused on an initialization strategy for NASA's StarLight mission, which consisted of two spacecraft forming a variable baseline interferometer. This paper presents a preliminary attempt in developing a methodology for FI of N spacecraft. A more comprehensive and complete treatment of the FI problem will be presented in [8].

A number of major technical challenges must be overcome in order to realize a practical solution to the formation initialization problem for N distributed spacecraft. First, any candidate algorithm must guarantee formation acquisition using limited field-of-view sensors. Second, formation attitude maneuvers must not violate sun-angle constraints.[1] Further, any candidate FI algorithm must result in an efficient search procedure that mitigates the probability of collisions.

The remainder of this paper is organized as follows. In the next section we discuss in detail the challenges inherent in the N-spacecraft formation initialization problem. We then present a solution of the FI problem based on a coordinated three-stage sky search procedure. Next, we discuss how our algorithm naturally leads to sub-formations and present the logic required to join these sub-formations. Next, we apply our FI algorithm to a realistic five spacecraft scenario using NASA's Terrestrial Planet Finder (TPF) mission as a baseline

[1] A typical imaging mission involves spacecraft carrying sensitive optical hardware that cannot withstand prolonged sun exposure. As a result, certain formation attitude maneuvers are prohibited.

and present some simulation results. Finally, we conclude and discuss some directions for future work.

II. The Formation Initialization Problem

In this section we discuss the characteristics of the N spacecraft formation initialization problem. In this paper, formation initialization (FI) is defined as the process of using limited field-of-view on-board sensors to establish communications among the formation members and to acquire the relative positions and velocities of a set of distributed spacecraft.

The FI algorithm developed in the sequel is based upon a set of assumptions that are divided into the following categories: dynamic constraints, spacecraft/sensor characteristics and controller/estimator characteristics. We now discuss each category in detail.

A. Dynamic Constraints

We assume that each spacecraft in the formation is a rigid body in which the rotational and translational motions are decoupled. The number of spacecraft in the formation is arbitrary. Further, we assume that the spacecraft are located in deep space where ambient disturbances such as gravity fields and aerodynamic effects are negligible. As a result, the free translational motion of the system consists of the center-of-mass of each spacecraft following a straight-line trajectory with constant velocity relative to an inertial observer.[2]

B. Spacecraft/Sensor Characteristics

We assume that each spacecraft is equipped with a limited field-of-view Autonomous Formation Flying (AFF) sensor [1]. The AFF sensor functions as the "eyes" of the spacecraft by providing the means to measure inter-spacecraft (i.e., relative) positions and velocities. Specifically, the AFF is a GPS-like sensor consisting of one transmitter that emits a conical beam pattern with a central angle of $2\theta_{FOV}$ and three receivers with a combined reception pattern essentially identical to the transmission pattern. Inter-spacecraft range is determined from transmission delay, while phase differences between the three antennas provide inter-spacecraft bearing angles.

The AFF is a distributed sensor; it requires a transmitter on one spacecraft and three receivers on another. Therefore, for the AFF sensor to function the spacecraft must each fall within the transmission/reception pattern of the other simultaneously. This configuration is referred to as a "front-to-front lock" or an F/F lock.

For the AFF sensors to obtain an F/F lock the following two constraints must *both* be satisfied

$$\theta_i = \arccos(\vec{b}_i \cdot \vec{e}_{ij}) \leq \theta_{FOV} \quad (1)$$

$$\theta_j = \arccos(\vec{b}_j \cdot \vec{e}_{ji}) \leq \theta_{FOV}\,. \quad (2)$$

Here $\vec{b}_i$ denotes the AFF bore sight vector (a unit vector along the centerline of the conical AFF beam pattern) of spacecraft i, denoted S/C_i, $\vec{e}_{ij}$ denotes the unit vector from the center of the AFF on spacecraft i to the center of the AFF on spacecraft j, denoted S/C_j, θ_{FOV} denotes the half-cone angle of the AFF antenna beam pattern, and $\cdot$ denotes the standard Euclidean dot product. The angles θ_i and θ_j are shown in Fig. 1. See also Fig. 2. We further assume that the AFF antenna beam has enough range for any FI scenario considered.

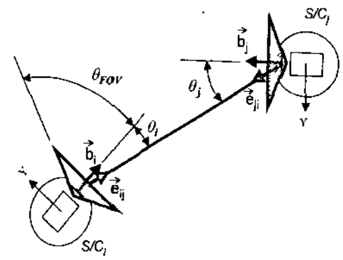


Fig. 1. Geometric Variables in F/F Lock Constraints (1) and (2)

We assume that each spacecraft is equipped with a functional inter-spacecraft communication link and that all inter-spacecraft communication is done instantaneously. Each spacecraft is equipped with a sun-shield to protect sensitive optical hardware from direct sunlight. For the sun-shield to provide adequate protection, the attitude of each spacecraft is subject to certain sun-angle constraints. In particular, the sun-shield normal of each spacecraft must remain within a specified angle of the sun-line. Here we assume a constraint angle of 25°. The AFF sensor is located at the edge of the sun-shield so that the AFF FOV is not clipped or distorted by the sun-shield. Each spacecraft is also equipped with a star-tracker that provides accurate inertial attitude knowledge. The maximum rotation rate of each spacecraft is limited due to star-tracker rate limitations. In the simulations to follow, we assume a maximum allowable angular rate of $0.25°/s$. Finally, a body-fixed reference frame is affixed to the center of mass of each spacecraft with the x-axis pointing normal to the sun-shield, the z-axis along the AFF boresight, and the y-axis chosen to complete the right-handed triad. See Fig. 2.

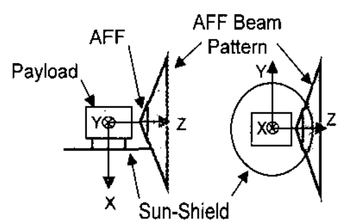


Fig. 2. Body Frame and AFF Location for Generic Spacecraft

C. Controller/Estimator Characteristics

We assume that all spacecraft maneuvers are performed kinematicly[3] and that all required Δv's are instantaneously delivered. Each spacecraft is assumed to have full attitude and translational control capability. Translational maneuvers without a direct relative state measurement available are permitted. Further, we assume that relative state knowledge does not significantly degrade over the period of FI.

[2] Although solar pressure will cause the motion of each spacecraft to deviate from its force-free trajectory, over the time scale required to initialize the formation (a few minutes to an hour), the motion of each spacecraft is approximately rectilinear.

[3] This is equivalent to assuming that the formation control law has "infinite bandwidth."

D. Major Challenges of FI

Given the characteristics of the FI problem discussed above, we now summarize the major technical challenges inherent in initializing a set of distributed spacecraft:

1) FI must be accomplished for a set of N spacecraft using limited FOV Autonomous Formation Flying (AFF) relative position/velocity sensors.
2) A front-to-front (F/F) sensor lock must be registered before relative state information between two spacecraft is established. Typical AFF beam patters and the F/F sensor lock geometry are shown in Fig. 1.
3) Certain spacecraft attitudes are prohibited due to sun-angle constraints.
4) FI must be accomplished in such a way that the probability of spacecraft collisions is mitigated and fuel consumption is not excessive.

In the next section we present a solution to the FI problem that addresses each of these issues.

III. FI ALGORITHM FOR N SPACECRAFT

In this section we present a methodology for initializing a set of N distributed spacecraft with limited FOV AFF sensors and arbitrary initial conditions. Our solution to the FI problem is based on a coordinated three-phase sky search consisting of (1) an in-plane search, (2) an out-of-plane search, and (3) a near field search. It is important to note that due to the F/F AFF sensor lock requirement, a full 4π steradian sky search performed by each spacecraft is necessary but *not* sufficient to guarantee formation initialization.

In order to assure that the spacecraft see each other simultaneously during the sky search, the set of N spacecraft are first arbitrarily divided into two groups. The AFF boresights are parallel within a group and anti-parallel (i.e., 180° out-of-phase) between groups. See Fig. 3 for a 3:2 partition of a five-spacecraft initialization scenario. The two groups are denoted $\mathcal{G}_A$ and $\mathcal{G}_B$ in the sequel. Note that this decomposition of the set of spacecraft into two distinct groups with anti-parallel AFF boresights is possible because the inertial attitude of all spacecraft is assumed known. We now discuss each phase of the coordinated sky search in detail.

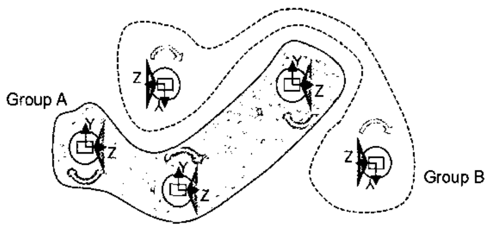


Fig. 3. Decomposition of Five Spacecraft in Anti-Parallel Boresight Groups

A. In Plane Search (IPS)

The IPS begins by dividing the set of N spacecraft into $\mathcal{G}_A$ and $\mathcal{G}_B$ as discussed above. Further, the local body-fixed x-axis (normal to the sun-shield; See Fig. 2) of each spacecraft is pointed toward the sun. Note that an attitude maneuver for each spacecraft is required to initialize IPS. Once all the spacecraft in $\mathcal{G}_A$ and $\mathcal{G}_B$ are properly oriented, each spacecraft begins rotating about its respective x-axis with angular rate Ω. The net effect is that the spacecraft within a group perform synchronized rotations. See Fig. 3. The question immediately arises as to how many rotations each spacecraft should perform during IPS; we will demonstrate in the sequel that at most 1.5 revolutions are required.

The sky coverage subtended by the AFF FOV during IPS for a single spacecraft is shown in Fig. 4. Note that the two shaded regions, called *complementary cones* (CC), are not swept out during IPS. Referring to Fig. 4, if the half angle of the complementary cone is denoted θ_C, then the total solid angle subtended by both complementary cones is

$$\begin{aligned} \Psi_C &= 2\int_0^{\theta_C}\int_0^{2\pi} \sin\theta \, d\phi \, d\theta \\ &= 4\pi(1-\cos\theta_C)\,. \end{aligned} \quad (3)$$

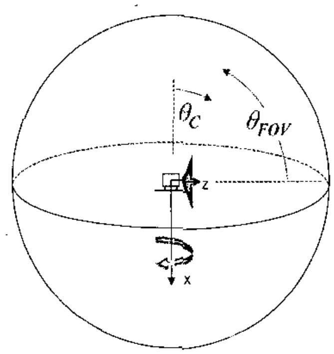


Fig. 4. Sky Coverage During IPS

Recalling that a sphere subtends a full 4π steradian, the amount of solid angle swept out by the AFF sensor in a full revolution is given by

$$\begin{aligned} \Psi &= 4\pi - \Psi_C \\ &= 4\pi\cos\theta_C\,. \end{aligned} \quad (4)$$

In this analysis we will assume that $\theta_C = 20°$; as a result, the AFF sensor for a single spacecraft subtends 94% of the sky during a single revolution.

To recapitulate, the IPS phase of the sky search consists of each group of spacecraft, $\mathcal{G}_A$ and $\mathcal{G}_B$, performing synchronized rotations about the sun-line with a fixed angular rate for 1.5 revolutions.

B. Out of Plane Search (OPS)

If after the 1.5 revolutions of IPS all N spacecraft have not found one another,[4] then the FI algorithm proceeds to the OPS mode. At this stage 94% of the sky has been searched by the groups $\mathcal{G}_A$ and $\mathcal{G}_B$. The OPS mode is initialized by commanding each group of spacecraft to return to their initial IPS attitudes with an additional 180° rotation about the x-axis (i.e., bore sights still anti-parallel) with all angular rates nulled

[4] Recall that the coordinated sky search is set up in such a way that spacecraft from $\mathcal{G}_A$ can only acquire spacecraft from $\mathcal{G}_B$ and vise-versa. The *complementary* interaction between the two groups of spacecraft is an essential feature of our algorithm.

(i.e., $\Omega = 0$). If control is assumed perfect during IPS, then the start of OPS is identical to stopping all the spacecraft after the 1.5 revolutions of IPS.

The goal of the OPS phase is for each group of spacecraft to sweep out their respective complementary cones. However, due to sun-angle constraints, unlimited rotations about the body y- and z-axes (See Fig. 2) are not permitted. Recall that we assumed the maximum allowable angle between the sun-shield normal (i.e., the x-axis) and the sun line is $\pm 25°$ and that the x-axis is initially aligned with the sun line. To search the two complementary cones under the $\pm 25°$ sun-angle constraint, all spacecraft from $\mathcal{G}_A$ perform a 25° tip followed by a $-50°$ tip about their body-fixed y-axes. Assuming that the half angle of the CC is $\theta_C = 20°$ (See Fig. 4) it follows that the above attitude maneuver *does not* search out the entire 40° CC.[5]

To complete the search of their CC's, each spacecraft in $\mathcal{G}_A$ must rotate 180° about the sun line (body x-axis) and then perform a 50° tip about the body y-axis.[6] It is critical that all attitude maneuvers done by spacecraft in $\mathcal{G}_A$ are performed in the *opposite* direction by the spacecraft in $\mathcal{G}_B$. For example, when a spacecraft from $\mathcal{G}_A$ tips 25°, a spacecraft in $\mathcal{G}_B$ tips by $-25°$. See Fig. 5.

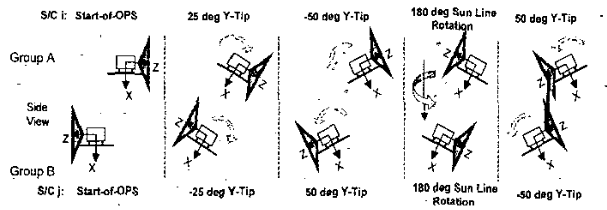


Fig. 5. OPS Maneuvers for Spacecraft in Groups A and B.

In summary, in the OPS phase of the sky search all S/C execute coordinated tips about the y-axis and rotations about the sun line to search the complementary cones while maintaining the sun-angle constraint.

C. Near Field Search (NFS)

If all spacecraft have not been acquired at the end of OPS, the search mode returns to the beginning of IPS, and the IPS and OPS phases are repeated. In the unlikely case that all the spacecraft have not been found, the FI algorithm proceeds to the Near Field Search (NFS). Since the AFF is located at the edge of the sun-shield, there is an AFF to spacecraft center-of-mass offset.[7] The near field is defined as the unsearchable region adjacent to each spacecraft due to this offset. See Fig. 6.

[5]Although it may be possible to temporarily relax the sun-angle constraint and search out the entire 40° CC with a single attitude maneuver, we have assumed that this constraint cannot be relaxed.

[6]Note that the actual tip angle required to fully cover the CC is given by $\tan^{-1}(\cos\theta_{FOV}/\sqrt{1-2\cos^2\theta_{FOV}})$. That is, for $\theta_{FOV} = 70°$ the spacecraft must initially tip at least 21.3° to cover the CC. As a result, it is possible to specify values for θ_{FOV} and the sun constraint angle such that the CC cannot be fully searched.

[7]Recall that this offset is required to prevent the sun-shield from clipping the AFF signal.

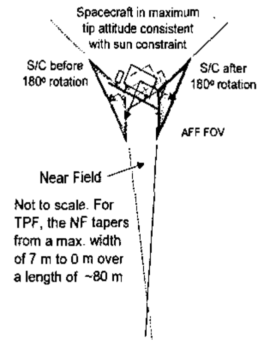


Fig. 6. Geometry of Near Field

The NFS search is initialized by commanding all spacecraft to return to their initial attitudes with zero angular rate. The spacecraft then wait for a time $t^* = \frac{L}{V_{max}}$ where L is a characteristic near field length and v_{max} is an upper bound on initial relative translational rates. The idea is to let the initial non-zero translational rates naturally let the spacecraft drift out of the near field. If there are still S/C that have not been acquired after waiting t^* seconds, then all remaining "lost" S/C are commanded to perform a translational maneuver in the anti-AFF boresight direction (i.e., along the -z body-axis) with a Δv of magnitude $2v_{max}$.[8]

In summary, the NFS phase of the sky search involves waiting for a time t^*, and then if needed, commanding an anti-boresight translational maneuver for all unacquired spacecraft.

IV. Sub-Formations and Join Logic

In this section we discuss how the problem of initializing a set of N distributed spacecraft is reduced to one of joining a set of (multi-spacecraft) sub-formations. Here we define a *sub-formation* as a subset of two or more spacecraft that have obtained relative translational state knowledge as a result of an F/F lock. Sub-formations are a natural consequence of the temporal order inherent in initializing a set of $N > 2$ spacecraft.[9] A formation is initialized in an aggregate manner, in much the same way as a complex macromolecule is constructed from simpler component atoms or as a crystal precipitates from solution.

The FI process naturally leads to the following two classes of sub-formations:

1) **Formation Set (FS)** A FS is defined as a sub-formation that uses active control to maintain constant inter-spacecraft ranges. Spacecraft belonging to the FS behave as a virtual rigid body. The first two spacecraft that acquire one another in the FI process form the kernel of the FS. Any other spacecraft that attains a F/F lock with a spacecraft in the FS is then brought into the FS by performing a suitable Δv to null its velocity relative to the FS.
2) **Knowledge Set (KS)** A KS is defined as a sub-formation in which no active control is used to main-

[8]This assures that each spacecraft will not be trapped in the near field after the translational maneuver has been performed.

[9]For example, spacecraft A first acquires spacecraft B, followed by spacecraft A or B acquiring spacecraft C, and so on.

tain relative spacecraft positions. However, relative state knowledge is propagated to avoid collisions and for use in eventually joining sub-formations. The kernel of the KS is formed when a second pair of spacecraft, neither associated with the FS, find one another. Any other spacecraft that attains a F/F with a spacecraft contained in the KS immediately joins the KS.

In order to conserve fuel, spacecraft in the KS do not perform translational maneuvers to null their relative velocities. The rationale is that as KS spacecraft will eventually have to join the FS, and to do so will need to cancel their relative velocities with respect to the FS, it is wasteful to impose an additional Δv to "rigidize" the KS. However, collision detection within the KS is performed, and if a collision is imminent, immediate corrective action is taken.

All spacecraft not yet in a sub-formation are considered elements of the *Lost set* or (*LS*). The distinction between the FS and the KS is illustrated in Fig. 7.

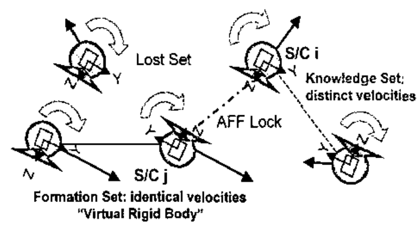


Fig. 7. Difference Between Formation and Knowledge Sets

We now discuss the logic required for joining a set of distinct sub-formations. The join logic used for a five-spacecraft scenario[10] ($N = 5$) is shown in Fig. 8. In actuality, the join logic table in Fig. 8 is an exhaustive list of all possible scenarios for a formation with $N \leq 5$.

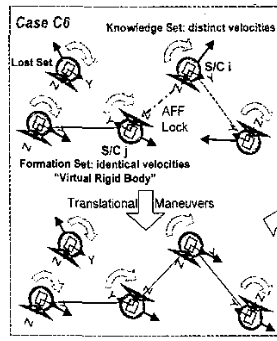
A representative example of the sub-formation join logic consider Case 6, illustrated in Fig. 8. Here S/C_i in the KS and S/C_j in the FS attain a F/F lock. As a result, the formation set is enlarged to include S/C i *and* all spacecraft in its associated knowledge set. To join the FS, all spacecraft in the KS perform a translational maneuver to null their velocities with respect to the FS. At the conclusion of these maneuvers, the five spacecraft consist of a four spacecraft FS moving as a virtual rigid body, and a single lost spacecraft yet to be acquired. The other eight scenarios listed in the join logic table can be described in a similar manner.

V. Application to TPF and Simulation Results

The formation initialization algorithm is demonstrated in simulation for five, 700 kg class spacecraft. Each spacecraft has a 15 m diameter sun-shield and a single AFF sensor located on the edge of its sun-shield.[11] A 7.5 m AFF offset from the spacecraft center of mass produces a near-field with a characteristic length of 80 m. The AFF sensor half-cone angle is 70°. Also, the sun-shield normals must remain within

[10]Although we have assumed $N = 5$, this is not a restrictive assumption as the join logic can be readily scaled to the case where N is arbitrary. The difference is that multiple knowledge sets can occur when $N > 5$.

[11]The sun-shield is also modeled as a rigid body.



Case	S/C i	S/C j	Action
C1	LS	LS	If FS==Null Set FS -> FS U {i} U {j} Else KS -> KS U {i} U {j}
C2	LS	KS	KS -> KS U {i}
C3	LS	FS	FS -> FS U {i}
C4	KS	KS	Continue Search
C5	KS	LS	KS -> KS U {j}
C6	KS	FS	FS -> FS U {i} U KS KS-> Null Set
C7	FS	LS	FS -> FS U {j}
C8	FS	KS	FS -> FS U {j} U KS KS-> Null Set
C9	FS	FS	Continue Search

FS : Formation Set KS : Knowledge Set LS : Lost Set

Fig. 8. Join Logic Table for Sub-formations with Illustrated Example

25° of the sun line. The spacecraft processor runs at 1 Hz. We reiterate that the simulation is kinematic, that is, perfect control is assumed. However, the FI guidance algorithm will be eventually integrated into a high-fidelity, kinetic simulation as part of a complete formation mission demonstration.

The spacecraft are initially separated by up to 300 m with relative speeds of up to 12 cm/s. The initial conditions were chosen to ensure that the OPS phase is entered. We noted during a Monte Carlo analysis that initialization was nearly always completed in the IPS phase. This fact is not surprising as IPS covers 94% of the sky. With five spacecraft, even though one spacecraft may be in the Complementary Cone or the Near Field of another, both spacecraft often lie within the IPS region swept out by a third spacecraft.

The FI algorithm simulated is a slight variant on the algorithm presented in this paper. The IPS phase consists of only one revolution of the spacecraft, followed by the OPS and then the NFS.

The results of the simulation are shown using a three view format. See Figure 9. The upper right window, called the Sun View, shows the spacecraft as viewed from the Sun. The lower right window, called the Spacecraft View, is a close up of one spacecraft. The maneuvers that comprise the three phase sky search are most easily seen in this view. The Oblique View is an overall view of the formation. In the Sun and Oblique Views, shaded cones emulate each spacecraft's AFF FOV. Finally, the time elapsed and the current phase of the sky search are shown in the upper right.

At the beginning of the simulation, the spacecraft align their x-axes with the Sun. The z-axes (AFF boresights), are aligned according to their group assignments. After this initial alignment, IPS commences. At approximately twelve minutes, as shown in Fig. 9, the bottom two spacecraft shown in the Oblique View see one another. A line joining the spacecraft indicates an F/F lock. Since these are the first two spacecraft to attain an F/F lock, they become the kernel of the formation set. Subsequently, both spacecraft in the formation set will be traveling through space as a virtual rigid body. The white lines trailing each spacecraft indicate their inertial translational motions.

At 14 minutes the upper two spacecraft in the Oblique View of Fig. 9 see one another and form a knowledge set. There are now two sub-formations consisting of two spacecraft each.

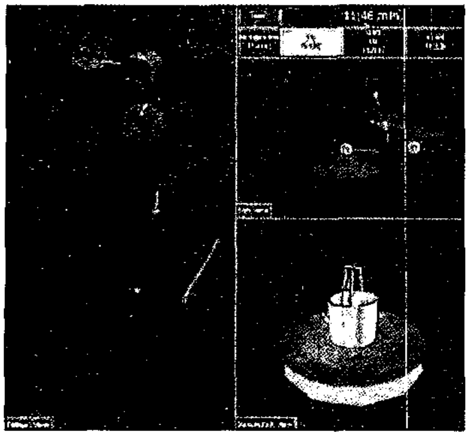


Fig. 9. TPF FI Simulation at Approx. 12 Minutes.

At approximately 16 minutes, as shown in Fig. 10, a spacecraft in the knowledge set sees the last lost spacecraft. The lost spacecraft immediately joins the knowledge set. The upper three spacecraft of the Oblique View now comprise a knowledge set and the bottom two spacecraft comprise the formation set. Note the kink in the white trail of the spacecraft second from the bottom of the Oblique View in Fig. 10. The kink corresponds to the translational maneuver that was necessary to form the formation set.

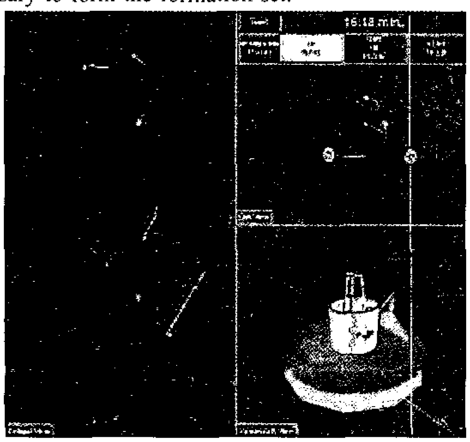


Fig. 10. TPF FI Simulation at Approx. 16 Minutes.

At 24 minutes IPS is complete and no new F/F locks have occured. Since the formation set does not contain all five spacecraft, OPS is initiated. During the first tip of 50° in OPS, a spacecraft in the knowledge set and a spacecraft in the formation achieve an F/F lock. This F/F lock is shown the Oblique View of Fig. 11 as the longer, diagonal line. As can be seen in the Sun View, some of the spacecraft have tipped their AFF cones towards the reader, while others have tipped their cones away from the reader. An F/F lock between the knowledge and formation sets occurs at 28 minutes and 40 seconds. After the appropriate translational maneuvers to null relative velocities, the formation is fully initialized. Since the formation has been completely initialized during the Out-of-Plane phase, the Near-Field phase is not required.

VI. Conclusion

In this paper we have developed an algorithm for initializing a set of N distributed spacecraft located in deep space. Our

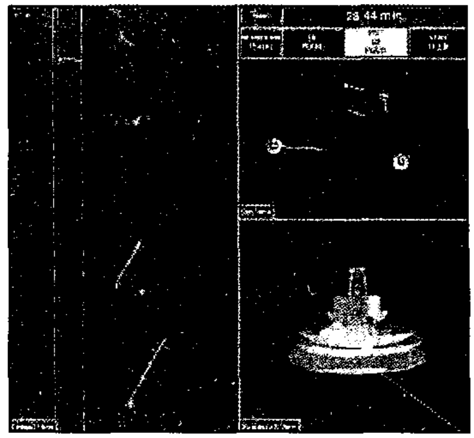


Fig. 11. TPF FI Simulation at Approx. 29 Minutes.

solution to the formation initialization problem is based on a three-stage sky search procedure consisting of (1) an in-plane search, (2) an out-of-plane search, and (3) a near field search. Moreover, realistic mission constraints such as limited FOV AFF sensors and sun-angle restrictions are explicitly considered. Another important feature of our solution is that the FI problem for N spacecraft is naturally reduced to the simpler problem of initializing a set of sub-formations. Finally, we demonstrated the performance of our algorithm in simulation by using NASA's five spacecraft Terrestrial Planet Finder mission as a baseline. In less than a half hour all five spacecraft were found. During Monte Carlo simulations, FI was typically completed during IPS, that is, in less than 24 minutes, and no failures of the algorithm occured. Details of an analytic proof guaranteeing formation initialization will be presented in [8].

Acknowledgment

This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to gratefully acknowledge Bill Breckenridge and Asif Ahmed for their valuable contributions to the work described in this paper.

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