Solar Sail Deployment Mechanisms: Bots with Variable Separation Vector and Inter-Boidal Force

Deya Sinha Roy, Souvik Maity

Abstract

The exploration of the vast dimension of the universe has made human race make extensive use of propellants for space expeditions, especially in long duration voyages. The application of solar sails, which derive momentum from solar radiation pressure, thus undergoing continuous acceleration, has apparently solved this problem. Yet, it has been observed that numerous solar sails fail to deploy in space, when needed; and the required area-to-mass ratio remains unachieved, rendering the solar sails useless. The idea of using bots, with behavior similar to boids, in deploying a solar sail is what this paper proposes. This can purportedly solve the aforementioned problem of failed deployments. The paper initially proposes the concept of time dependent boid behavior in an extended model of boids, which wholly works towards the first proposed deployment mechanism of solar sails, in bots. Later, another extended model of the boids system has been proposed, which introduces the idea of inter-boidal forces, to play a role in another deployment mechanism. The paper also describes the solar sail deployment mechanisms right from its stowed configuration to its deployed configuration, mentioning the challenges for each of the two ideas.

Keywords

Solar sail, deployment, boid, inter-boidal force, bots, collision avoidance.

Introduction

Solar Sailing is a space craft propulsion system that uses solar radiation pressure to obtain acceleration. Large ultra-light, mirror-like sails derive propulsion due to the momentum imparted to it by the incident and reflected photons. This gives rise to a low but continuous thrust. Solar sails make up a “propellant less” propulsion system making it ideal for long-duration space voyages. It also possesses the ability to conduct orbital plane changes. By adjusting the direction of the sail relative to the Sun, it produces acceleration in the desired direction. This acceleration when directed opposite to the velocity, gives rise to an efficient de-orbit mechanism at the end of the life time of the craft. Space missions are hoping to exploit these features of solar sail extensively. In 2010, JAXA (Japanese Aerospace Exploration Agency) launched IKAROS (Interplanetary Kite-Craft Accelerated by Radiation of the Sun) became the first craft operating on controlled solar sailing.

However, the thrust produced by Solar Radiation Pressure (SRP) is very small, i.e. of the orders 9 micro Newton/ sqm. The efficiency of solar sails depends on its area/mass ratio. This is why the technology becomes inefficient for satellites of considerable mass and is only applied to CubeSats, as of now.

Evolution of science has witnessed humankind getting inspired from elements of nature to find sustainable solutions for their own selves, all through bio-mimicry. Ant, a creature which doesn’t communicate verbally, has provided us with an algorithm for determining the shortest distance from a source to a destination. An ant, there, can be considered as individual element with limited intellectual capabilities. The kind of behavior which the individual creature subconsciously exhibits, leads to an intelligent pattern which can solve complex problems. The process of developing an intelligent system using a set of ordinary individual elements, by making them follow their normal routine, with no centralized controlling agent, gives rise to swarm intelligence.

One such intelligent system is the system of boids. [1] Introduced by Craig Reynolds, this system can be interpreted as collaboration between bio-mimicry and swarm intelligence. Using the flight behavior of a flock of birds, boids consider each bird as an individual element and analyze the behavior of a single bird. Drawing an analogy with the particle system and the states of matter, a collaborative and competitive environment involving numerous bots which show behavior and movement characteristics similar to boids, can lead to a model wherein these bots align themselves according to the instantaneous variable internal forces and steers. The possible swarm-shape changing capacity of these boid-like bots, which are collectively considered as a swarm, leads to designing of deployment mechanisms for Solar Sails.

The mechanism ideas proposed in this paper aim to design solar sail sail deployment methods by applying the behavior of boids in bots, to design a deployable solar sail, which is compact and fits in the limited size available in the launch vehicle and occupies a large area once deployed in space. Thus, making solar sails an efficient propulsion system for satellites of any mass. This paper proposes the idea of gradually increasing the separation vector in a system of boids and the concept of inter-boidal forces in a system of boids, for divergence, convergence and shaping of the flock. The paper ideates the use of these 2 principles, separately, in bots, for deployment of Solar Sails, explaining the two procedures entirely.

Background

1. Mechanism in solar sails

The concept of solar sailing uses the Sun’s electromagnetic radiation to propel a space craft. Quantum of packets of energy, also called photons, impart a momentum to the sail as they are absorbed or reflected by its surface. As per Newton’s second law of motion, direction of force imparted on the photons due to the sail is in the direction of the change of momentum. Accordingly, the force of reaction on the sail is in opposite direction, as shown in figure 1. In an ideal solar sail, which is 100% reflective, the direction of resultant force is normal to the surface of the sail. According to Les Johnson, Grover A. Swartzlander, AlexandreArtusio-Glimpse in “An overview of Solar Sail Propulsion within Nasa” [5], this is analogous to the lift force acting in an aeroplane, it is referred to as ‘optical lift’.

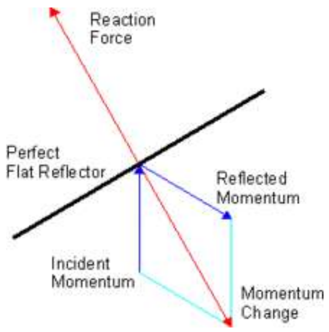


Figure 1: Impact of photons on Solar Sail

According to Michael D. Souder and Matthew West in "Solar Sail Technology for Nanosatellites" [6], for the force acting on an ideal sail, magnitude of force acting on it is given by:

$$F_r=2PA\cos^2\alpha$$

Where α: The angle between sail normal and direction of incoming photons
A: The area of the sail
P: Radiation pressure

The radiation pressure term follows the inverse square law with respect to the distance between the sun and the sail. At a distance of 1 au from the sun, value of P is 4.67×10^{-6} Nm^{-2} [6]. The optical lift generated by the photons is very small, and is of the order of 9μN for a $1m^2$ sail. [6]

Therefore, the corresponding acceleration generated:

$$a_r=2P(A/M)\cos^2\alpha$$

Where M: Mass of the solar sailing craft

Hence, at altitudes exceeding 800Km where solar radiation pressure exceeds aerodynamic drag, an ideal solar sail produces a continuous acceleration, in the direction normal to the surface of the sail. The magnitude of the acceleration thus produced depends on the area to mass ratio.

2. *Materials used in solar sails*

Beside area to mass ratio, the other factors that affect the performance of a solar sail are the optical property of the sail material, the mechanical property of the sail material and the sail geometry. The sail size depends on payload mass and nature of trajectory. About 1-20g/m^2 areal density is needed in general cases, according Roman YaKezerashvili's "Solar Sail: Material and Space Environment Effects" [7].

If areal density, $s=m_s/A$, where $m_s$is the mass of the solar sail and A is its area:

$$s=p*d$$

Where p is the density of the material and d is the thickness of the sail [7]. To maintain a low value of s, a thin film of a low density material is chosen. According to SalvatorSantoli in "Carbon Nanotube Membrane Solar Sail", [8] commonly used materials are Kapton with a thickness of 7.5μm offering an area density of 15g/m^2 and Mylar which is 1μm thick and 2g/m^2 dense. They are given 500amstrongs Aluminum coating (Reflectivity between 0.8 and 0.9).

As the sail materials are very thin, it cannot resist solar compression or bending. It can only withstand tension. The metallic sail of reflective Aluminum layer and emissive Chromium layer of aurora project is better in terms of rigidity. However, for deployment purposes polyester films are preferred [8]. To keep the film taut, certain sail types use a continuous spinning motion. Others use supporting trusses, ribs and booms. The booms used are ultra-light and flexible. Fiber-reinforce composite shell, graphite rod or inflatable tubes are used for this.They have an area density of 14g/m^2; thus making the net area density of the boom-film assembly to be approximately 4.5g/m^2,according to Lars Herbeck, ChristophSickinger, Michael Eiden, Manfred Leipold in "Solar Sail Hardware Developments" [9]:

3. *Structure and deployment of solar sails*

Solar sail designs of three types have been currently developed: heliogyro, spinning disk and square sail. According to Kathleen Howell in "Solar Sailing"[10], the prime features of the different types of sails are:

- Heliogyro: This type of sail consists of several reflecting vanes extending from a central hub as shown in figure 2. They continue to spin to maintain the rigidity of the vanes. Orientation of the sail is maintained by tilting vanes.

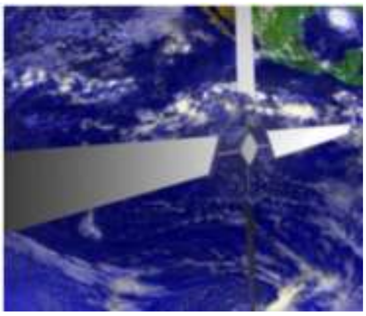


Figure 2: Solar Blade Solar Sail

- Spinning disk: This is a disk shaped rotating sail. The payload is placed at the central truss as shown in figure 3. Rigidity of the sail is maintained by light-weight tension lines.

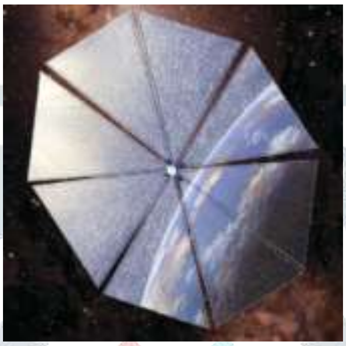


Figure 3: Cosmos1 Spinning Disk Sail

- Square Sail: This type of sail consists of a flat reflective surface which is maintained at its position by spars and booms as shown in figure 4. Tipping Vanes or smaller sails at the corners are used to achieve attitude control.

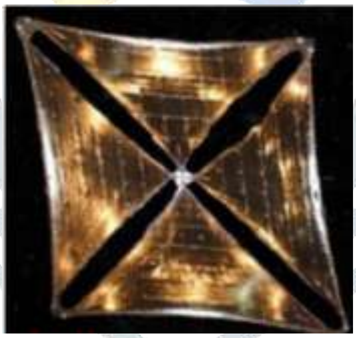


Figure 4: Nano Sail D Square Sail

The solar sail deployment systems currently in use are,

- A central deployment module consisting of rozlled flexible lightweight booms and folded sail material. Once released, usually from a heated container, strain energy causes the booms to unroll and the sail films unfurls with it. Sometimes the booms used are flexible at room temperatures and rigidize in the low temperatures of the space. This system is used mainly in square sail type. Eg. DLR/ESA [9].
- The sail film is connected to an inflatable tube truss. The tubes are compressed in stowed configuration. They are inflated by supplying gas during deployment. They elongate and the sail film unfurls with it. Eg. Cosmos. [9]
- The heliogyro crafts use the centrifugal force developed due to the spinning motion of a roller around which the sail vanes are wrapped causes them to unfurl. [10]

4. Attitude and trajectory control

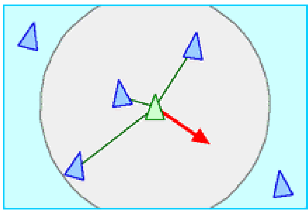
The solar sailing craft can change its trajectory by changing the orientation of the sail with respect to the sun. If the solar sails are oriented such that acceleration is produced in the direction of velocity, orbital energy increases and the craft can rise to higher orbits. If the direction of acceleration is opposite to orbital velocity then the craft gradually de-orbits at the end of its lifetime. [6]

Attitude control is achieved simply by displacing the center of solar radiation pressure from the center of mass by altering the sail configuration, which produces torque. [6]

5. *Behavior of boids*

Every bird in a flock follows a set of three rules [1] to maintain the flock – “Collision avoidance” for separation, “Velocity matching” for alignment and “Flock centering” for cohesion [3], as shown in figures 5, 6 and 7. A system of boids can be considered to be a single swarm of individual and discreet elements, they being birds. In the figures 5, 6 and 7, the individual behavior of the boid in green had been analyzed with respect to its neighboring boids, in blue.

All boids have limited vision; that is, a visibility sphere which is defined by a variable (mostly user defined), whose value is usually five times the size of the boid itself. Only those boids which are present inside the visibility sphere, shown in grey, of the boid are visible to it.



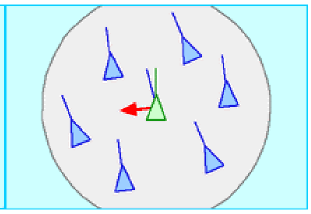


Figure 5: Collision Avoidance [3] Figure 6: Velocity Matching [3]

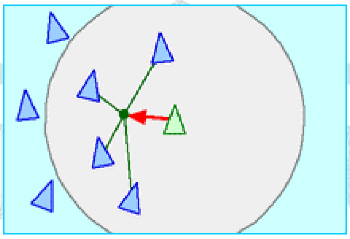


Figure 7: Flock Centering [3]

In Figure 5, the boid in question tries to distance itself from other boids in the visibility sphere, when they seem too close to it. This is to avoid collision with the boids in the vicinity of itself. The separation vector which directs the steering force on a boid, for collision avoidance can be implemented in numerous ways. [4]

At the same time, in the process of collision avoidance, the boid keeps in mind its required position – at an average distance from the other boids inside the visibility sphere, as shown in Figure 7. [4] These two behaviors keep the boid in its optimized position.

For the direction and velocity of the flight, the alignment of the boid is such that its direction corresponds with the average alignment of the boids inside the visibility sphere.

This pattern is predicted keeping in mind there are no external obstacles to be faced in the way of the boids. These three individual behaviors of boids make the entire flock maintain its flight, thus displaying a swarm behavior.

6. *Analogy of a system of boids with the three states of matter*

As shown by AntonieDutot, Damien Olivier and GuilhelmSavin in their paper, titled – “Collaboration and competition in boids simulation with predation” [2], a physical analogy between the system of boids and the states of matter can be drawn. Initially, a lower threshold attraction factor between boids – ϱ_1, and a higher threshold attraction factor – ϱ_2, are defined. [2]

These threshold attraction factors are so defined that –

a. If the attraction factor between boids is lesser than ϱ_1, cohesion between the boids in the system ceases to exist, like gases. Thus, the motion of the boids gets randomized and the boids start moving in directions to fill the environment. Refer to Figure 8.

b. If the attraction factor lies between ϱ_1 and ϱ_2, groups of boids are formed inside the environment. The cohesion between certain boids brings them closer, and these groups of boids scatter in the environment, with collaboration between the systems. This is analogous to liquid state. Refer to Figure 9.

c. If the attraction factor is more than ϱ_2, the boids in the system come close as the cohesion between them increases. They finally form a single mass, cease motion and become compact. This is analogous to solid state. Refer to Figure 10.

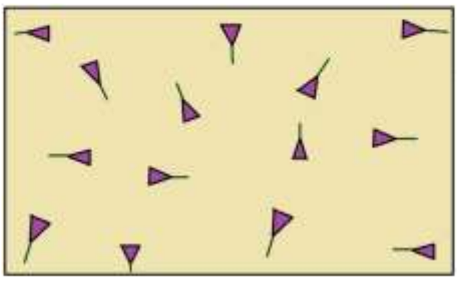


Figure 8: Analogous to the Gaseous State

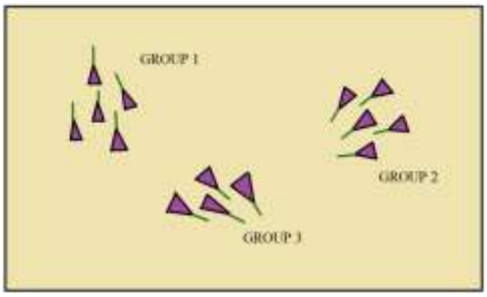


Figure 9: Analogous to the Liquid State

Figure 10: Analogous to the Solid State

I. Inter-boidal force

An extended model of boids can bring in the concept of “Inter-boidal Force”, over the proposed “Others attraction” rule. Consider two boids, A and B, of the same system. A force, **F(A→B)** is defined between boid A and boid B, which is directly proportional to f (d), which is a function of the distance, d, between A and B; and directly proportional to a factor of attraction, γ (A→B), which is defined on boid A for boid B. This force is directed from A towards B. Therefore, the force acting on boid B because of boid A –

$$\mathbf{F(A\rightarrow B)} = \gamma\,(A\rightarrow B) * f\,(d) * \mathbf{m}$$

Where, **m** is the unit vector along the line joining the centers of A and B, from A towards B.

Following the convention, negative magnitude values of **F (A→B)** imply attraction, while positive magnitude values imply repulsion between the boids. While the boids duly follow their three aforementioned principles for flock movement, this force simultaneously acts on all the boids in the system, irrespective of their visibility sphere. Figure 11 shows the individual inter-boidal forces **F(1)**, **F(2)**, **F(3)** and **F(4)** acting on boid 5, due to boids 1, 2, 3 and 4 respectively, which are all in the same system. The resultant inter-boidal force on boid 5 is a vector addition of **F(1)**, **F(2)**, **F(3)** and **F(4)**.

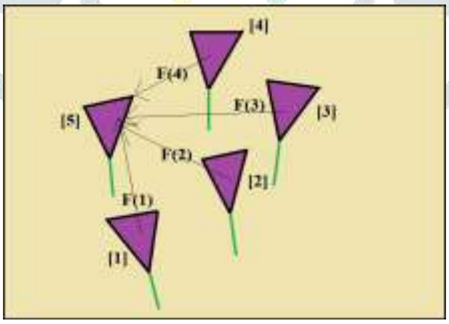


Figure 11: Inter-boidal forces acting on a boid

The net inter-boidal force acting on any boid X, in the system, therefore is –

$$\mathbf{F\,(X)} = \sum \mathbf{F\,(n\rightarrow X)}$$

Where n: All the other individual boids in the system respectively.

This force acting on a boid doesn’t hamper the self-velocity magnitude sense and the own sense of alignment of the boid, as it tends follows the “Velocity matching” property at all times. The resultant velocity and direction of the boid on the other hand changes, due to the acceleration generated by the inter-boidal force. The inter-boidal force can help in modeling the “Collision avoidance” property and makes the shape of the flock flexible. These inter-boidal forces help the boids diverge or converge as a flock. The shape formed depends on the individual values of γ (n→X)andf (d). The value of γ (n→X)can either be a pre-defined constant or be dynamically modified depending on the co-ordinates of the individual boids to obtain a desired symmetry and shape of the flock.

The values of the factors of attraction between the corresponding boids in the vicinity need to be so maintained that the third property – “Flock centering” is maintained for all the boids.

II. Variable Separation Vector in Collision Avoidance

Let us consider a set of boids of species B. Each element b_i of the set has three variables associated with which are: position vector $\mathbf{p_i}$, velocity vector $\mathbf{v_i}$ and up vector $\mathbf{u_i}$.

A vision e is defined for the flock. A boid can interact with other elements of the set present within the sphere of radius e. The interaction between a boid and other boids in its sphere of visibility is governed by three kinds of steer: separation or collision avoidance, alignment or velocity matching, cohesion of flock entering.

Let there be n boids b_1, b_2, b_3 …… b_n within the visibility sphere of an element b_i.

Separation steer $\mathbf{s_i}$ on b_i is defined as [4]:

$$\boldsymbol{s_i} = \sum_{j=1}^{n} -(\boldsymbol{p_i} - \boldsymbol{p_j})$$

Alignment steer of b_i is defined as [4]:

$$\boldsymbol{m_i} = \sum_{j=1}^{n} \frac{\boldsymbol{v_j}}{n}$$

If $\mathbf{c_i}$ be the position vector of the centre of density of the n number of boids visible to b_i, then

$$\boldsymbol{c_i} = \sum_{j=1}^{n} \frac{\boldsymbol{p_i}}{n}$$

Thus, the cohesion steer acting on the boid b_i is defined by [4],

$$\boldsymbol{k_i} = \boldsymbol{c_i} - \boldsymbol{p_i}$$

Thus, the change in $\mathbf{p_i}$ in time Δt is given by,

$$\Delta \boldsymbol{p_i} = S\boldsymbol{s_i} + M\boldsymbol{m_i} + K\boldsymbol{k_i}$$

Where, S, K, and M stand for separation factor, cohesion factor and alignment factor respectively, defined globally for the set. $S\boldsymbol{s_i}$ is called the Separation Vector, $M\boldsymbol{m_i}$ is called the alignment vector and $K\boldsymbol{k_i}$ is called the cohesion vector.

The new position attained by b_i in time Δt, $\acute{\boldsymbol{p}}_i$ is -

$$\therefore\ \acute{\boldsymbol{p}}_i = \boldsymbol{p_i} + S\boldsymbol{s_i} + M\boldsymbol{m_i} + K\boldsymbol{k_i}$$

The instantaneous velocity of b_i is given by -

$$\boldsymbol{v_i} = \boldsymbol{dp_i}/dt$$

The instantaneous velocity can also be defined as -

$$\boldsymbol{v_i} = \Delta\boldsymbol{p_i}/\Delta t$$

Where ($\Delta t \rightarrow 0$)

In a proposed extended model of the same, separation factor, S, be defined as a function of time, making the magnitude of separation vector vary with time. This is done while maintaining the value of M and K at constants between 0 and 1. Therefore, the separation vector be S(t). In this case,

The change in $\mathbf{p_i}$ in time Δt, is given by,

$$\Delta \boldsymbol{p_i} = S(t)\boldsymbol{s_i} + M\boldsymbol{m_i} + K\boldsymbol{k_i}$$

The initialization of the values of K and M and the definition of S(t) as a function of time are the parameters which hold the key to the motion and shape of the flock. This makes the steering vector, $S(t)\boldsymbol{s_i}$ - vary with time. If S(t) is so defined that it increases with time, the magnitude of separation vector shall exceed the magnitude of cohesion vector eventually and the flock shall tend to diverge; and vice versa. A situation where all boids have zero boids inside their visibility area is where the flock disintegrates. The function S(t) and values of K and M should be defined so as to avoid this condition.

Description of Mechanisms for Ideas

1. Structure of the solar sail used in the proposed model

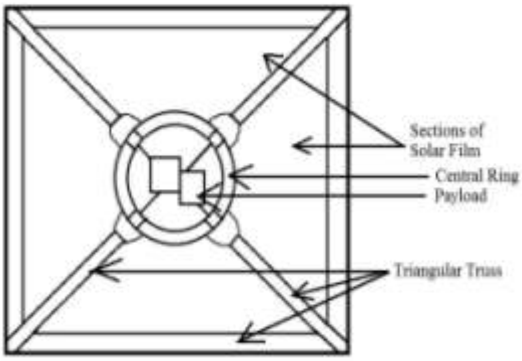


Figure 12: Concept Structure of the Solar Sail

- **Structure of the sail**: A square sail consisting of four triangular sections is to be used. Each triangular section is supported by a triangular truss, as shown in figure 12.

- **Supporting truss**: The supporting truss is made of ultra-light material. Small lengths of rods of minimal thickness are hinged together to form long foldable members. Alternatively, coilable booms can be used for this purpose.

- **Sail film**: The sail film comprises of four triangular sections. Each triangular section is composed of two layers of film fixed rigidly to the triangular truss.

- **Bots**: Bots are present in two opposite sections of the sail as shown in figure 14. These bots exhibit boid behavior. They are stationed inside the two layers of the solar film, with their height equaling the gap between the two film layers, as shown in figure 13. The two opposite sections have two independent bot systems, wherein boid behavior in one section does not depend on the boid behavior in the opposite section.

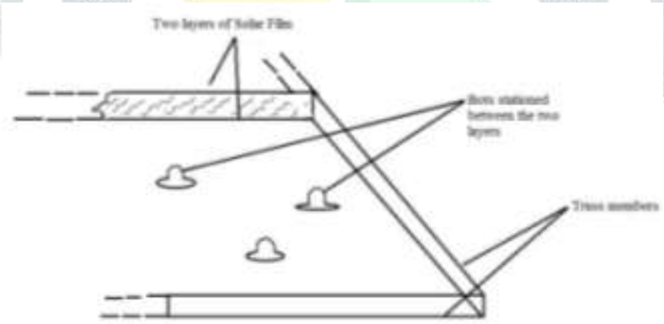


Figure 13: Bots stationed between two film layers

- **Central Ring**: This is where the payload is attached to the solar sail.

2. Stowed configuration

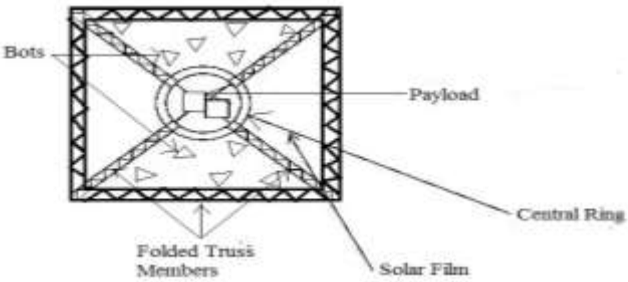


Figure 14: Concept Diagram of Stowed Configuration

In the stowed configuration of the solar sail, the truss members are folded or collapsed and the sail film is folded or rolled on the central ring so as to occupy minimum volume as shown in figure 14. The farthest ends of the sail film are attached to the ends of the truss members, before the truss members are folded or collapsed.

The bots have been placed on the two opposite sections of the solar sail, as complete expansion of the foldable supporting trusses or coilable booms in any two opposite sections will roll out all the four sections.

3. Deployment mechanism

The bots are set in motion, by assigning an initial acceleration and subsequent velocity to the bots, when the solar sail separates from the launch vehicle, for an in-orbital deployment.

The bots are initially fed with the boid properties – Collision avoidance, velocity matching and flock centering.

i. Deployment mechanism using inter-boidal force –

These bots need to be designed with the capability to apply inter-boidal force of the required magnitude, in the required direction. The inter-boidal force can be of pressure-thrust or of any workable nature, which is one of the challenges for this mechanism. This should be done keeping in mind that they be light-weighted and do not affect in attainment of the required area-to-mass ratio of the solar sail. The idea to feed the bots with boid behavior shall make the motion of the bots easy to maintain, as they can self-align and self-position themselves, like individual elements in a swarm.

With subsequent motion of the bots, as a swarm or a flock, the attraction factor between the bots is to be defined, such that the bots maintain their flock centering property at all times. With a gradual increasing pattern in the magnitude of attraction factor between the bots so that the magnitudes of the inter-boidal repulsion forces increase, the bots remain in an accelerated motion. The attraction factor needs to be so defined that the flock diverges with increasing inter-boidal distance and the bots approach the film wall at the edges, with maximum velocity. Thereby, the mechanism calls for dynamic attraction factors, depending on the desired magnitude and direction of velocity and acceleration of the bots in the system.

As the bots move with continuous acceleration, they push against the film wall at the edges. This acts as a movable obstacle for the bots. On collision with the film edges, there is a change in momentum of the bots. This, in turn, plays a role in the resultant velocity of the individual bot. In these cases, the magnitudes of attraction factor by the other bots in the system, on the bot in question, need to be dynamically changed with time so that the resultant velocity of the bot is directed as it would have been in the absence of the film edge. This mechanism directs the motion of the bots in the swarm.

The normal reaction on these walls causes the film to unroll from the central ring, as the inter-boidal distances keep increasing. As the sail unfurls, the supporting members expand with them, as depicted in figure 15.

ii. Deployment mechanism using variable separation vectors –

This extended model of boids, using variable separation vector, in two dimensions can be used conveniently for controlled deployment of solar sails.

The boid characteristics are applied on autonomous bots which are stationed within two layers of solar film. At the point of activation of the bots an initial velocity directed towards the outer wall of the film is imparted to the flock. The separation factor is initially defined as an increasing function of time. With this, $\Delta \boldsymbol{p}_i$ shall increase with time. The flock begins to diverge by pushing against the wall of the stowed solar film. This force causes an expansion in area with simultaneous unrolling of film and unfolding of supporting members. The unfolding of the supporting member ensures the unfurling of the sail film in the sections which do not contain a bot-system. The value of e, which governs the visibility area, should be high enough for the bots to cover the entire unfurled area of the solar sail section.

After complete deployment, the supporting trusses are interlocked using a locking mechanism. The total time taken to deploy the sail, T, depends on the rate of change of S, with time.

4. Post deployment

Once the sail film has fully unfurled and the truss members have unfolded to their maximum lengths, these members are locked to maintain their configuration. Now the solar sail assumes its square shape, as the farthest ends of the sails have previously been attached to the ends of the trusses. The boid behavior in the bots is deactivated, keeping the mechanism of applying inter-bot force active. The attraction factor between the bots is adjusted, so that they cluster together (analogous to the molecules in solid state of matter) in their respective sections, with the clusters' centers of mass at co-ordinates which keep the solar sail in equilibrium.

The orientation of the sail with respect to the Sun plays an important role in the navigation of the sail craft. Attitude of the craft is controlled by displacing the center of mass from the center of pressure. This produces a torque, causing the craft to rotate.

The bots present between the solar sail films, now as a cluster, can be used to manipulate changes in the center of mass. Whenever an orientation change is desired, the cluster of bots in the two sections can be positioned with the clusters' centers of mass at the deemed co-ordinates in their respective sections. These co-ordinates, in the opposite sections, are calculated based on the shift required in the center of mass of the solar sail with respect to the center of pressure, for a torque to be produced in the desired direction. The tipping vanes, which are usually employed to control orientation of a square sail, will therefore not be required.

Solar radiation pressure often causes the thin solar films to compress or develop wrinkles over a course of time. Under such circumstances the boid characteristics can be activated again. Accordingly defining the attraction factors, the bots can be aligned in a way, so as to produce tension in a desired direction, to make the solar sail taut again.

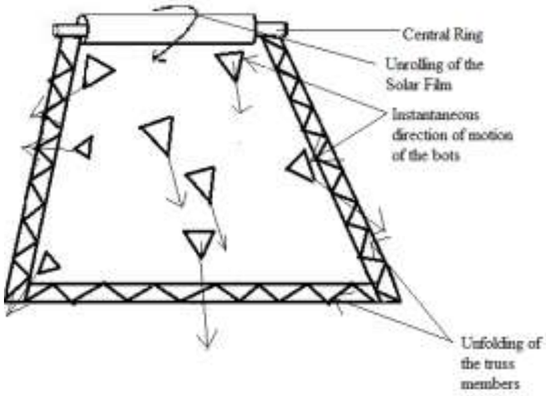


Figure 15: Concept Diagram of Deploying Mechanism

CHALLENGES

The major challenges anticipated in implementing these ideas have been identified to be –

i. Mechanism using inter-boidal force

1. The mechanism that shall enable the bots to start motion between the sail film layers, when activated.
2. The mechanism which shall impart inter-boidal forces between the bots.

ii. Mechanism using variable separation vector

1. The mechanism to enable motion of the bots between the sail film layers, when activated.

A possible solution to the above challenges is the application of tensegrity bots with boid characteristics and mechanism to either impart inter-boidal force or show variable separation vector.

REFERENCES

[1] C.W. Reynolds, " Flock, herds and schools: A distributed behaviorial model", in SIGGRAPH, 1987, Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques, New York, NY, USA: ACM, 1987, page 25-34.

[2] A. Dutot, D. Olivier, G. Savin, "Collaboration and competition in boids simulations with predation"

[3]Source:http://cs.stanford.edu/people/eroberts/courses/soco/projects/2008-09/modeling-natural-systems/boids.html. Retreived: 2nd June, 2015 .

[4] C. Hartman, B. Benes, "Autonomous Boids", Computer Animation and Virtual Worlds, 2006, Published online in Wiley InterScience, page 199-206.

[5] Les Johnson, Grover A. Swartzlander, Alexandre Artusio-Glimpse in "An Overview of Solar Sail Propulsion within Nasa", Published in Springer, 2014, XIII, 987 p., 607 illus

[6] Michael D. Souder, Matthew West, "Solar Sail Technology for Nanosatellites", in AIAA/AAS Astrodynamics Specialist Conference and Exhibit, 18-21 August 2008, Honolulu, Hawaii

[7] Roman Ya Kezerashvili, "Solar Sail: Material and Space Environment Effects", http://arxiv.org/abs/1307.7327, Cornell University Library, 28 July 2013

[8] Salvatore Santoli, "Carbon Nanotube Membrane Sails: A Challenge for Extremely fast Space Flight", in "Carbon Nanotubes" Book published in www.intechopen.com on March 1, 2010

[9] Lars Herbeck, Christoph Sickinger, Michael Eiden, Manfred Leipold, "Solar Sail Hardware Development", European Conference on Spacecraft Structures, Materials and Mechanical Testing, Toulouse 2002

[10]Kathleen Howell, "Solar Sailing", Purdue University, http://www.insightcruises.com/pdf/sa07_slides/Solar_Sailing.pdf