Mission Concept for Autonomous on Orbit Assembly of a Large Reflector in Space

Dario Izzo[†] Lorenzo Pettazzi [§] and Mark Ayre [†]

[†]ESA, Advanced Concepts Team, ESTEC Keplerlaan 1, Postbus 299,2200 AG, Noordwijk
[§]ZARM, University of Bremen, Germany

contact: dario.izzo@esa.int

Abstract

Self organisation is the result of a set of dynamical mechanisms whereby structures appear at a global level due to the interactions amongst lower-level components. Self assembly can be considered a sub-domain of self organisation, where lower-level components actually form structures out of themselves rather than inert elements of the environment. Observing the instances of self-organisation and self-assembly widespread in nature we can marvel at the robustness of the processes and the complexity of the structures that are produced. In this paper we draw inspiration from these processes to face the problem of the conceptual design of an assembly scheme for a large reflector in space. ESA, JAXA and NASA have identified several new mission concepts, including very large aperture telescopes and solar power collection and transmission systems, that require the construction of a large reflective surface in orbit. As long as the characteristic dimension of the reflector array is increasing the necessity of an in-situ assembly of different components by means of an automated procedure arises. Besides, the design criteria for hypothetical reflector array elements are identical to those for solar sails - low mass per unit area (high assembly loading), high specular reflectance (high sail efficiency), and stowability in a tight volume. In this paper the feasibility of reflector elements doubling as solar sails for a sailing transfer up to the reflector construction site from a lower orbit and then self-assembling into a large reflector is investigated. Such a strategy potentially reduces significantly the number of launches required to place a reflector array into position. The phase of the assembly process that requires proximity operation between several components is then studied relying upon novel techniques based on swarm intelligence.

Introduction

Self assembly can be considered a sub-domain of self organisation, where lower-level components actually form structures out of themselves rather than inert elements of the environment. Both self organisation and self assembly are ubiquitous throughout nature: taking a tour through the natural world from the smallest to largest scales, we can observe the self-organisation of subatomic particles into stable atomic configurations, crystal formation, nanoscale self organisation of peptides and polymer chains, organisation of polymers into larger functional structures, DNA replication and virus shell assembly (Berger & Shor, [4]). At a cellular level, processes such as morphogenesis and mineral deposition lead to a multitude of hiearchical structures such as muscle, bone, cutin, bark etc, whilst morphallaxis (Hotz, [12]) allows the structural reordering of cells without proliferation. At the level of whole individual organisms, we can see the construction of incredibly complex nests by eusocial insects such as Termites (Luscher, [16]) and Tropical Wasps (Jeanne, [14]). Some species of social insects can also self-assemble into structures composed of their own bodies - for example in the chain formation of Oecophylla longinoda (Holldobler & Wilson, [11]). Observing these instances of self-organisation and assembly we can marvel at the robustness of the processes and the complexity of the structures that are produced. Completely unsentient artifacts such as biological cells achieve advanced global structure, and their orchestrated actions are superbly tolerant in the face of pertubations such as random cell death or malfunction (Kondacs, [15]). The mechanisms involved in natural self organisation are very attractive to a number of engineering fields.

For engineering purposes, a self assembling system can be defined as one where order and structure arise without human intervention. Self assembly can also be characterised as the formation of large structures out of smaller components. These two descriptions of self assembly immediately reveal why engineering the ability to self-assemble into future space structures would be very desirable. Firstly, there are upper mass and volume limits associated with the delivery of structural elements to space. For example, the International Space Station has been delivered to orbit over the course of many launches for the simple and obvious reason that it could not be contained within the fairing of a single launch vehicle. This is coupled with the fact that there will be many construction situations in the future where a human presence is not possible or practical: from a cost perspective, the assembly of large structures by astronauts even in Low Earth Orbit (LEO) is prohibitively expensive (Shen et al., [21]). Remote supervision and control of assembly could be possible from the ground for LEO and near Earth instances, but obviously further afield would also be impractical due to typically long communication delays. There are a number of mission concepts that will require automated assembly. The development of automated on-orbit assembly has been identified as a key requirement by the AURORA program (ESA's exploration program). Advanced mission concepts being developed also rely upon the use of swarms of satellites - examples are the APIES and ANTS architectures (EADS, [9]; Curtis et al., [7]). Under the gossamer spacecraft initiative NASA has identified several new mission concepts, including very large aperture telescopes, large deployable and inflatable antennas, solar sails and large solar power collection and transmission systems. The most ambitious group of structures that require in-situ assembly of a number of separate components in space are a number of SPS concepts such as those described in (Carrington, [5]). The concepts can be divided into three primary classes, all of which are conceived of as being not only extremely massive and composed of literally thousands of components, but also placed at geostationary orbit far from the Earth. A typical mass for such a structure would be 18000 MT.

At a systems engineering level, the work done to date in realising automated assembly in space can be best represented by the SOLAR (Self Assembly for Space Structures) project - this is based around the FIMERS concept described in (Shen et al., [21]), a system for self assembly of a space structure using Intelligent Reconfigurable Components (IRCs), and a number of free-flying FIbre-rope Matchmaker Robots (FIMERs). All the IRCs are envisaged to be equipped with GPS/Galileo receivers and wireless communication, an on-board computer that will control the information gathering processing and communications, canonical connectors to dock with other components and FIMER units, a position and orientation sensory system, an on-board controller for topology discovery, action planning, communication with FIMERS and other IRCs and monitoring the progress of assembly, and auxiliary connections for fluid-gas pipes and electric connections so the structure can operate as a unified whole when fully assembled. The assembly of the IRCs is conceived as being mediated by one or more FIMER robots (figure 3). Each FIMER robot consists of a pair of robot 'heads' attached by a thin fibre that can be reeled in or out by the heads. Each head can fly autonomously and (de)dock with any IRC or other FIMER robots. Each head is equipped with a rotational/translational thruster system, a motor to manage reeling of the fibre, GPS/Gallileo, wireless communications, a robotic manipulator arm, and a reconfigurable connector. The self-assembly process is orchestrated by the Digital Hormone Model (DHM) developed for the CONRO reconfigurable robot system (Castano et al., [6]). Summarised simply, IRCs signal that they wish to dock with each other, and then call a FIMER for help. The FIMER heads attach one to each IRC and provides docking guidance through reeling them together. The canonical connectors will use infra-red to provide guidance signals for alignment in the docking process, as used in the CONRO system (Rubenstein et al., [20]). The mechanics of pulling two IRCs together using the Fibre allow simplified control, naturally avoiding undesirable rotation. At this final stage, the manipulator arms on each head will be used to provide fine-grain control of the docking process. The connectors can detect their state and gathering this information allows the current topology of the structure to be determined. The IRCs then negotiate to decide on the next sequence of actions to take. The sequence of IRC assembly is embedded in the IRCs themselves. For a homogeneous system of IRCs, each IRC and it's connectors do not require unique identification and sequencing is not required. In the case of a heterogeneous set of IRCs, unique identifiers are used for each connector (for a semi-homogeneous set of IRCs, type-identifiers for generic components is sufficient).

Self assembly of a large reflector in GEO

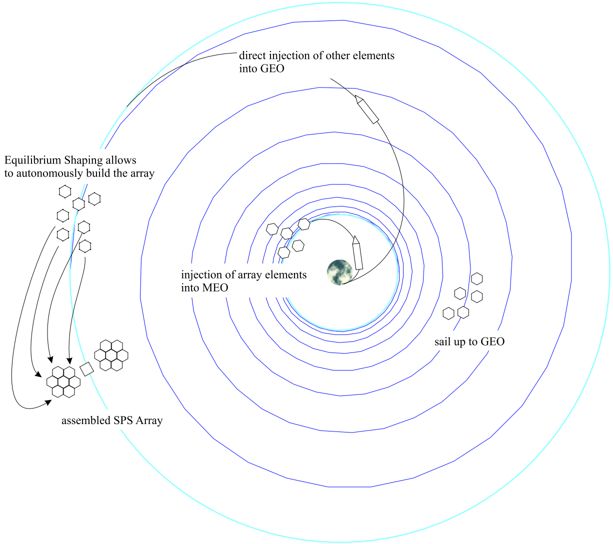


Figure 1: Illustration of the proposed assembly process for a SPS in Geostationary orbit.

We here propose a new concept to assembly large reflectors in the Geostationary orbit. The concept originated from the cooperation of Mission Analists and Biomimetic experts of the Advanced Concepts Team of ESA and tries to take advantage of behaviour based intelligent components (Ayre et al., [2, 3], Izzo and Pettazzi, [13]) to put and assembly a huge structure into Geostationary orbit. The design criteria for hypothetical reflector array elements are identical to those for solar sails - low mass per unit area (high assembly loading), high specular reflectance (high sail efficiency), and stowability in a tight volume. For this reason we explored the possibility of spiralling up from MEO to GEO the various homogeneous agents using the solar flux as propulsion system. The essential features of the reflector assembly scheme are shown in Figure 1. Initially, reflector elements are injected into a MEO orbit. These elements then separate from each other and deploy, and begin the spiral up towards GEO. Immediately prior to their arrival other required infrastructure (fuel tanks etc.) are delivered directly to the desired orbital position of the SPS array. When the elements arrive they start the self assembly sequence by forming larger and larger subgroups that eventually form the entire array. The autonomous and distributed path planning technique called Equilibrium Shaping (Izzo and Pettazzi, [13]) is used to drive the terminal assembly sequence. The MEO orbit injection height has to be sufficiently high to allow avoidance of the high-energy proton environment of the Van Allen belts so that the sail material, once deployed, avoid extensive damage due to charged particles. An altitude of 9000km would allow avoidance of the worst of the proton flux (which can reach 400 MeV): the peak electron flux occurs at higher altitudes (see Figure2), but is less of a problem due to the much lower momentums involved.

The following conceptual design follows from initial choices concerning the launch system used and the dimensions/geometry of the deployed array elements. These initial design choices are:

(i) Hexagonal array elements with a characteristic dimension of 100 m^2. This last number is estimated from a quote from McInnes & Eiden, [18]. For a 2.5 km by 3.5 km elliptical reflector such as that envisioned for the SPS concept of Mori et al. [19], this results in a requirement for approximately 850 array elements. Figure 3 shows one possible configuration composed of 861 elements and a total surface area of 7.456 km^2.

(ii) Use of the Energia launch system with some modification to the Payload Bay in order to op-

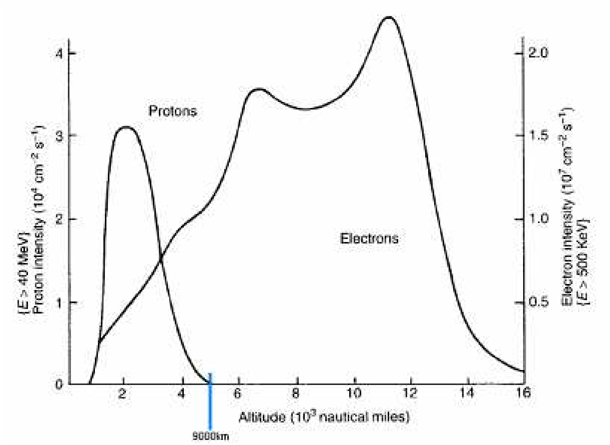
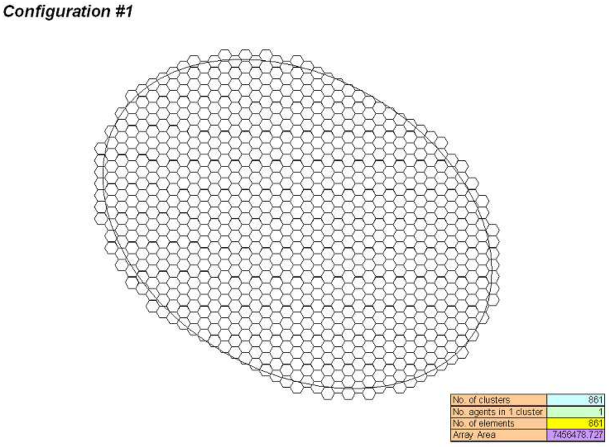


Figure 2: Van Allen belt proton and electron intensities as a function of altitude.

timise the number of launches required. Only a superheavy lifter such as Energia would be suitable due to the huge number of array elements required. The Energia launcher design is capable of lifting 88,000 into LEO, and 18,000kg into GEO (with the Energia Upper Stage - EUS). The external payload fairing, in the original design, has a payload bay area of 37m (height) by 5.5m (diameter), although the available length is reduced by the presence of the EUS. As we will see due to the poor packing factor of the agent the payload bay has to be redesigned in order to take advantage of the spiral out.

Agent Preliminary Design

After initial consideration of the likely mass and volume associated with one array element compared to the mass/volume constraints of the Energia fairing, it is apparent that the payload capacity constraint of Energia in this instance is volumetric rather than massive. It is necessary to maximise the packing of array components to the greatest extent possible in order to achieve the most use of the payload mass capability. The array element geometry chosen to achieve this is hexagonal, comprising a central hub from which stem 6 rigid booms, as shown in Figure 4. This does not maximise the ratio of reflector area to boom length (maximised by a square sail configuration). However, hexagonal elements were considered primarily for packing purposes within the fairing, as their initial shape more closely conforms to a circular form.



No. of clusters	861
No. agents in 1 cluster	1
No. of elements	861
Array Area	7456478.727

Figure 3: A possible configuration of 861 hexagonal elements forming the elliptic reflector.

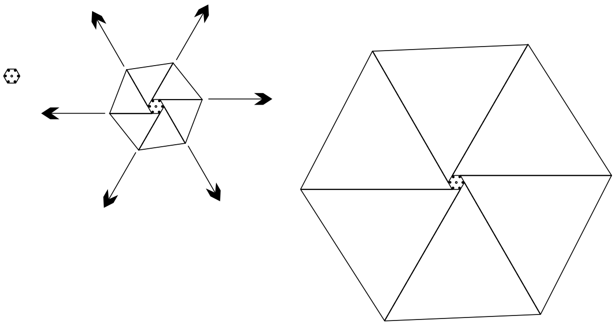


Figure 4: Deployment sequence of the single array element.

Extendable booms are guided during deployment from the stowed boom rolls by the outer edges of the hexagonal structure. On the boom tips are mounted the connector elements that allow docking with other array elements - These could consist of sexed connectors for one-sided reflector elements, or perhaps canonical hermaphroditic connectors if two-sided reflector elements are used. The deployment mechanism of the element makes use of Carbon Fibre Reinforced Plastic (CFRP) snap-boom technology, developed by DLR [Herbeck et al., [10]] for solar sail deployment. The boom is formed from two hemispherical halves that are joined at tapered edges - this results in a cross-section that approximates to a circle, and therefore has good structural stiffness and resistance to buckling. For stowage, the two hemispheres are pressed together to form a flat plate of material which can then be rolled, giving excellent packing density (see Figure 0.9). Deployment simply consists of unwinding the boom material off the roll, at which point the compressive forces holding the two halves together are removed, and the circular cross-section is regained. With these assumptions it is possible to make a preliminary assessment of the mass and the sail loading of the single array element as shown by Ayre et al. [3]. Accordingly to this last study we will assume, for each agent, a reference mass of $M = 310kg$ resulting in a sail loading of $36g/m^2$ which is a very high loading for a solar sail (current technology objectives for sail loading are around 10 [Herbeck et al., [10]]). However, this value is good enough for our requirement (sail-up to GEO from 9000) as we shall see.

For the Energia fairing with EUS, approximately 67 array elements could be integrated (assuming there is an unusable 2 m space at the leading tapered edge of the fairing, and a characteristic packing height of 0.32 [3]). This corresponds to a mass of around 21 tonnes, which is only 3 tonnes more than the GEO payload capacity of the launcher. Extrapolation from a performance chart in [Isakowitz et al., 2000] reveals that Energia (with the existing EUS design) could lift approximately 55-60 tonnes into a 9000 circular orbit. The current EUS therefore overperforms massively for this concept. We may envisage a redesign of the EUS such that the number of array elements per launch delivered to a 9000 km circular orbit is optimised - i.e. reduce the EUS size and capability to allow more array elements to be carried per launch. For this study we assume a redesigned EUS which increases the available payload bay length to 30 (the EUS length is reduced by 8.5m - approximately 45% of it's length excluding the nozzle). This allows 94 array elements to be stowed (assuming the same packing height as before), which gives a mass of 29071kg. As a first order approximation we assume that the delivery capacity of the EUS would be proportional to the volume of the body: thus the resized EUS is capable of delivering this payload to a 9000 circular orbit. A back of the envelop calculations shows that for the SPS concept of Mori et al. [19] the number of launches may be reduced from the 17 needed for a direct GEO insertion to 12 if we use the sail-up strategy.

Sailing from MEO to GEO

To establish the feasibility of the concept it is necessary to design a feasible transfer trajectory for the array elements to spiral up from the 9000km MEO orbit to a GEO orbit. There exist a growing number of studies on the global optimisation of solar sail trajectories, globally optimal results have recently been obtained using evolutionary neurocontroller by Dachwald [8]. However to establish the feasibility of our concept we consider a much simpler (sub-optimal) transfer based on the conventional wisdom that energy input to a sail trajectory should be positive wherever possible, and that the sail should be feathered for zero-energy input at all other times [Sands, 1961]. For a circular orbit, this gives the simple sailing strategy whereby the sail is oriented normal to the sun-line for the half-orbit where it is moving away from the sun, and parallel to the sun-line for the half-orbit where the sail is moving towards the sun. If we consider an approximate relation for the orbital transfer in which the thrust is aligned with the element velocity vector we obtain:

$$\dot{a} = \frac{2v}{\mu} f a^2$$

after integration this gives:

$$\Delta t = \left(\frac{1}{a_i} - \frac{1}{a_f} \right) \frac{\mu m_T}{2\bar{v}\bar{f}}$$

with $f = P_{eff} A \cos(\theta)$ where P_{eff} is the effective solar radiation pressure at 1 AU (the product of $P = 4.56 \times 10^6 Nm^{-2}$ at 1AU and the sail efficiency factor), and θ is the angle between the solar sail velocity and the sun-line. For the sail strategy mentioned above, the average force exerted on the sail by the sunlight, assuming a perfectly reflecting sail surface, during one orbital period is given by: $\bar{f} = \frac{2PA}{\pi}$. In this instance this is 0.02513 . For the array element design described previously, with a sail loading of 36 g/m^2, this yields a transfer time of 1.11 years (406 days). Because the trip-time is inversely proportional to the sail efficiency, this transfer time will of course be somewhat larger for less efficient sail surfaces. For a sail surface efficiency of 0.75, the trip time would extend to 540 days. In a real case a optimised trajectory would be used that takes into account also the limitation deriving from the attitude control capabilities. Nonetheless, this would not appear prohibitively long to invalidate the concept when compared to the likely length of the construction campaign of the SPS concept, which would likely extend to several years (one possible complication to this approach is the recent interest within the SPS community of using sail material that acts as a band pass filter for those segments of the solar spectrum that cause excessive heating at the EGT - the high UV and infra-red components of the spectrum. Using a sail material that is transparent to parts of the solar spectrum will of course reduce the amount of momentum that is transferred to the sail and increase the trip-time). During the transfer period, we can also evaluate the torque required to maintain the required attitude against gravity gradient effects. The average gravitational torque acting on the element during a whole period can be evaluated from the following formula (which considers the gravitational torque only in the orbital plane):

$$\mathbf{M} = \frac{3\mu\,(B-A)}{\pi r_0^3}\hat{\mathbf{h}}$$

where A and B are the moments of inertia of the solar sail out of plane and in plane respectively, and is the orbital radius. The max torque exerted during the whole transfer period is 0.1634 Nm. A deployable ballast mass system that allows sailcraft rotation around any axis through the centre of mass and parallel to the sail plane [Angrilli & Bortolami, [1]] could be used to counter this gravitational torque.

The self-assembly algorithm

Once the array elements reach the desired final orbit they have to start the assembly sequence to construct the large array (see Figure 3 for a possible configuration). In order to assess the possibility of performing such a task in a completely automated manner we developed and studied a behaviour based navigation technique inspired by collective robotics and named Equilibrium Shaping [13]. This allows the agents to autonomously plan their path toward the acquisition of a number of possible final relative configurations avoiding collisions. No inter agent communication is required and only the neighborhood sensed by each agent is used to evaluate the velocity desired by each agent. Once this is known a control system has to be designed to enforce the desired kinematical field. The Equilibrium Shaping accounts also for the gravitational environment allowing to exploit as much as possible ballistic trajectories rather than forced ones.

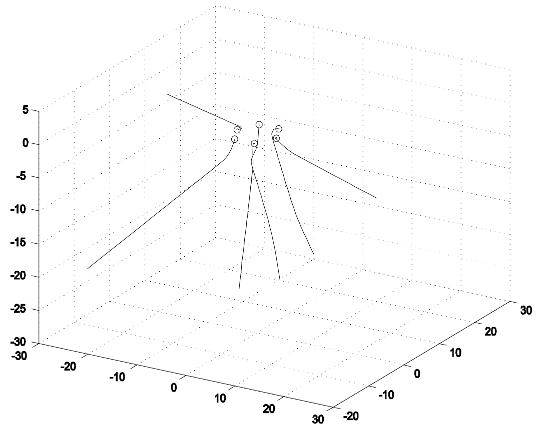


Figure 5: Desired trajectories of a swarm reaching a hexagon-shaped target configuration.

In Figure 5 and Figure 6 the path planned by a group of six agents reaching an hexagon formation around a seventh agent is shown as an example of the capabilities of the Equilibrium Shaping. Note that there is no position preassigned to the agents so that the agents autonomously decide which position to occupy in the hexagon. The eventual conflicts arising are solved in real time with no additional effort. A complete description of the technique can be found in the work by Izzo and Pettazzi [13].

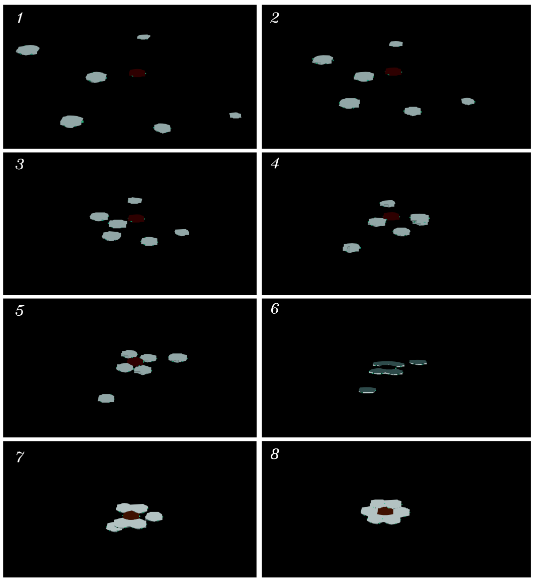


Figure 6: Storyboard for the autonomous assembly of an hexagon element via equilibrium shaping.

Toward more complex structures

Because of the mathematical details underlying the Equilibrium Shaping technique complex lattice geometries may not be "shaped"so that, alone, the Equilibrium Shaping could not be used to self-assembly a large reflector such as that needed for an SPS. To be able to build structures that are more complex than the ones allowed by this technique we have to abandon the possibility of using absolutely no communication or negotiation between the different agents and use some kind of hierarchical organization of the agents. Work is currently being undertaken by the Advanced Concepts Team on this issue, we here give a simple example on how this could be achieved. Assume to be able to group the various agents into seven groups of six and to pick other seven agents that we will call seeds. he seeds plan their path according to the Equilibrium Shaping obtaining a desired velocity $\mathbf{v}_s$. They do not need to communicate any information between them, but they do communicate their desired velocity to the other non-seed agents. These evaluate their desired velocity $\mathbf{v}_a$ using the Equilibrium Shaping in a frame attached to one of the seed so that they will eventually form an hexagon around the seed. The control system of these agents will try to track a velocity given by the sum of the two contributions: $\mathbf{v}_{tot} = \mathbf{v}_s + \mathbf{v}_a$. In this scheme each of the non seed agents need to communicate with the relevant seed to receive its actual desired velocity. By equipping each of the agent with wireless communication systems it is not difficult to imagine that this limited amount of communication may be achieved.

An example of the result that such an assembly scheme produces is given in Figure 7. In this case a number of 49 agents is divided into a group of seven seeds and seven groups of six normal agents. The path planning toward the final planar configuration is autonomously done by the 49 agents with no collisions and a good exploitation of the gravitational tidal forces.

Conclusion

A brief outline of a novel SPS self assembly construction concept based on the use of solar-sail technology and collective robotic behavioural path planning as been presented. The general scheme of the concept has been defined, and some preliminary calculations concerning some of the more critical parameters have been performed. The concept reduces the number of launches required by a significant amount, and hence could be an important step in reducing the total cost of an SPS system. A preliminary design of an autonomous self-assembly procedure is also presented introducing a behaviour based approach to the agent path planning problem.

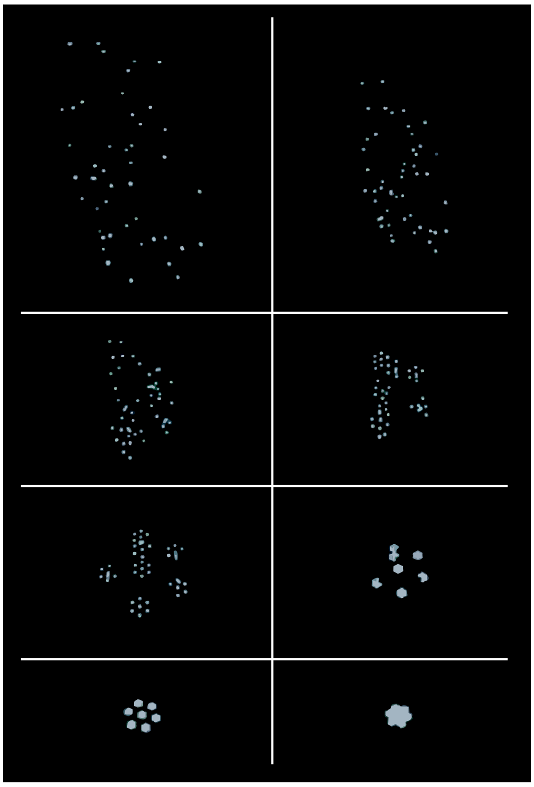


Figure 7: Assembly sequence for 49 agents applying the Equilibrium Shaping technique to a hierarchical group formed by seeds and normal agents.

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