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# SPATIAL MANAGEMENT OF LARGE CONSTELLATIONS OF SMALL SATELLITES

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***Анотація.*** *Згідно з прогнозами, внаслідок запланованого запуску угрупувань супутників, розміри яких дають можливість називати їх мега-угрупуваннями, кількість супутників на низьких навколоземних орбітах у найближчі роки зросте до понад 100 000 одиниць. Такі системи використовуються насамперед для здійснення спостереження за Землею і космосом, забезпечення глобальних комунікацій, а також глобальної безпеки й оборони. Проте, не зважаючи на їх ефективність, запуск та керування угрупуваннями супутників супроводжуються багатьма проблемами, серед яких потреба в удосконаленні міжсупутникових ліній зв'язку, налагодження бортового управління, встановлення надпотужних терміналів та шлюзів на Землі, уникнення зіткнень з іншими супутниками і космічним сміттям тощо. До сьогоднішнього дня не було запропоновано жодних системних моделей та інфраструктури для угрупувань супутників такого розміру. У статті підсумовуються ідеї розробленої Технології просторового захоплення (ТПЗ) і її високорівневої Мови просторового захоплення (МПЗ), а також досліджується їх ефективність в управлінні великими угрупуваннями супутників. Вбудовування взаємопов'язаних інтерпретаторів ТПЗ в усі супутники угрупування дозволяє перетворити його на інтелектуальну систему, здатну автономно вирішувати численні проблеми, зменшуючи зв'язок зі складними наземними антенами. У статті представлено декілька основних операцій, які можна здійснювати на угрупуваннях супутників. Серед них, зокрема, можливість трансляції повідомлень до цілого угрупування, збір інформації з усіх супутників, а також проведення реструктуризації всього угрупування. Виходячи з досвіду роботи з попередніми версіями ТПЗ, підхід, заснований на вірусоподібному покритті великих просторів, можна застосовувати навіть в університетських умовах. Використання рекурсивних сценаріїв у ТПЗ є набагато зручнішим за інші підходи, що, у свою чергу, відіграє важливу роль у зменшенні навантаження та уникненні втручання в інші космічні комунікації.*
***Ключові слова:*** *угрупування супутників та мега-угрупування, глобальні комунікації, спостереження за Землею та космосом, Технологія просторового захоплення, управління угрупуваннями, рекурсивні просторові сценарії, космічне сміття.*

***Abstract.*** *The number of satellites in low Earth orbits is predicted to grow over 100,000 in the coming years due to the launch of planned satellite constellations which are often called mega-constellations because of their expected size. They are appealing mostly for global communications, Earth and space observation, as well as for global security and defense. Despite their attractiveness, implementation of satellite constellations is connected with many problems. Among these problems are the necessity of advanced inter-satellite links, onboard management, high-duty Earth terminals and gateways, avoidance of collisions with other satellites and debris, etc. Up to now, no system models and infrastructures have been offered for such large fleets of satellites. The paper summarizes the developed Spatial Grasp Model and Technology (SGT) and its high-level Spatial Grasp Language (SGL), and investigates their applicability for management of large satellite constellations. Embedding cooperating SGL interpreters into all satellites allows to convert the whole constellation into an intelligent system capable of solving numerous problems autonomously, reducing communication with complex ground antennas. The paper shows some basic operations on satellite constellations including broadcasting orders to the whole constellation, collecting information from all satellites and emergent restructuring of the whole constellation. Based on the experience with previous SGT versions, the approach based on virus-like coverage of large spaces allows to implement it even within university environments. Recursive scenarios in SGL are much more compact*

*than under other approaches which may be important for reducing load and interference with other space communications.*
***Keywords:*** *satellite constellations and mega-constellations, global communication, Earth and space observation, Spatial Grasp Technology, constellation management, recursive spatial scenarios, space debris.*

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## 1. Introduction

The aim of this article is to show how numerous problems that emerge with the launch of large satellite constellations can be resolved with the help of high-level technology already tested on many distributed systems applications. The number of satellites in low Earth orbits is predicted to grow dramatically in the coming years due to the launch of planned satellite constellations. Despite their high attractiveness, implementation of satellite constellations is connected with many problems. The paper summarizes and investigates the developed high-level networking model and technology for their applicability in effective organization and management of large satellite constellations.

The article is organized as follows. Section 2 provides a summary of existing publications on satellite constellations and mega-constellations with their features and problems. These include proper management, the use of onboard intelligence, providing replacement, issues of effective communications which may be optical, complexity of ground antennas and gateways to monitor low orbit satellites, as well as the increase in space debris produced by constellation units when they are not de-orbited at the end of their service or after their failure. Section 3 summarizes the Spatial Grasp Model and Technology (SGT) which has already been tested on numerous applications and which may be useful for management of satellite constellations. General SGT ideas are also included, as well as the worlds where it operates and their integration, the high-level Spatial Grasp Language (SGL) used for the expression of recursive constellation navigation scenarios and its implementation in arbitrary large dynamic networks which can be integrated with any terrestrial and celestial systems. Section 4 shows how supplying satellites with SGL interpreters, which can communicate directly not only with each other as an integral system but also with the ground stations, may convert the constellation into a self-organized and entirely space-located system followed by significant simplification of ground antennas and reduction in their numbers.

Section 5 shows some basic operations over satellite constellations in SGL in a virus-like self-spreading parallel mode which include broadcasting executive orders to all satellites via direct and changeable communications between them, collecting and returning accumulated data by all satellites, and constellation repositioning and restructuring which may be emergent. Section 6 mentions more complex constellation operations effectively organized under SGT (some of them have been already explained in the recently published paper), which include tracing hypersonic objects and constant observation of ground infrastructures by LEO satellites despite their staying over ground points for a short period of time. More constellation operations will be shown in the new book whose planned contents have been already published. Section 7 concludes the paper, revealing some plans for further development of the approach and its broader application in large satellite systems, as well as the possibilities of quick implementation of the technology using the experience from its previous versions.

## 2. Satellite Constellations and Mega-Constellations

### 2.1. General Notions

Near-Earth space is becoming increasingly privatized, with the number of satellites in low Earth orbits predicted to grow dramatically from about 2,000 at present to over 100,000 in the next decade due to the launch of planned satellite constellations [1–4] which are often called mega-constellations because of their expected size [5–10], as symbolically shown in Fig. 1.

Figure 1 – Growing satellite constellations

They will enhance our daily communication, provide us with unending sources of new information and enable many new applications. Smaller and cheaper satellites, some of which are of the size of a briefcase, can be arranged in different configurations depending on their goal. Spacecraft constellations are appealing especially in three fields: 1 – communications (for global coverage), 2 – Earth observation (for near real-time measurements), 3 – space observation (for continuous monitoring). They offer worldwide communication links competing with terrestrial cellular networks.

### 2.2. Management Issues

With such a number of active elements in orbit, their management is a fundamental point of interest. Since constellations were not widely used in the past, not enough has been done in this respect. Proposed solutions fall into two main categories:

a) optimization of automatic satellite tracking (e.g., the download of telemetry);

b) automatic failure detection, so that the operator does not need to manually check the state-of-health of the satellite. Increasing automation onboard the spacecraft, which is not always easy due to the size of satellites, and carrying out prediction, planning, diagnosis, repair, etc. on ground would be of much help. The need for automation is also linked to the collision avoidance assessment and maneuver planning which is now largely manual. Mostly enabled by technology miniaturization, satellite constellations require a coordinated effort to face the technological limits in spacecraft operations and space traffic. There is so far no available cost-effective infrastructure that could withstand coordinated flight of large fleets of satellites.

### 2.3. The Need for Onboard Intelligence

There are a number of proposals concerning an onboard automated managements system based on artificial intelligence. In their implementation, some failures can be not only detected but also handled automatically towards a resolution along with a re-scheduling of the original plan. The main drawback of such proposals is the need for inter-satellite-links which is usually not affordable for low-cost strategies. Moreover, it implies intensive inter-satellite communication contributing to a crowded RF spectrum. The automatic re-planning decreases the ground workload, allowing the operator to concentrate more on the goal, rather than on the path to it.

### 2.4. Replacement Strategy and Variable Size of Constellations

Replacement (spare) strategy is an operational aspect that should be taken into account from the very beginning because such a strategy is the policy adopted by the operators in order to substitute failed or terminated satellites of the constellation. These spare satellites can be then placed into the constellation when there is the need for it. It makes the constellation size adaptable to the market reaction, although it is very difficult to predict how to configure the orbits in space avoiding multiple launches.

### 2.5. Communication Issues

Onboard automation is so far difficult to develop to the point that would allow fully autonomous fleet management because the large amount of satellites will need to communicate frequently with ground. Overcrowded RF spectrum may cause physical interference of adjacent RF signals. Sharing and integration between space and ground communication terrestrial networks will be effective enough. Efficient implementation of inter-satellite link should be done through routing algorithms, taking into account maximum available link time and remnant bandwidth to increase the total traffic capacity of the network in the presence of handover. A completely different approach to avoid RF spectrum overcrowding implies moving to the optical part of the spectrum. Optical communication promises higher data rates using smaller and lighter terminals, even though due its high sensitivity to atmospheric conditions it is more suited for free-space inter-satellite links rather than for satellite-to-ground ones.

### 2.6. Gateways and Antennas

High-duty, rugged and smart Earth terminals and gateways will be needed. Because of the size of LEO satellites that will soon fly, the speed at which they travel and variations in frequencies, tracking LEO satellites will be a challenging procedure. Any terminal or gateway communication with a LEO satellite will need to receive satellite positions on a regular basis, and this information is directed to terminals continually. All new LEO constellations will require gateways for tracking antennas, downloading data and sending information back to each satellite. Depending on the frequency, gateway antennas vary in size and complexity. The higher the frequency, the harder it is to position the antenna to track and communicate with each satellite. And the larger the constellation, the more terminals or gateways will be needed to maintain frequent communications with each satellite. However, delivering real-time interactive broadband communication services with a large number of LEO satellites and travelling at high speeds over the horizon requires significantly more complex networks and user terminals than GEO-systems. For example, antennas need to the track some moving satellites and the system needs to handle handover of communication sessions between satellites, whereas only one GEO satellite is required to serve its respective purpose. Constellations with inter-satellite links will require fewer gateways. These constellations will be able to maintain private satellite-to-satellite links and minimize the need for continual communication from each satellite to the gateway.

### 2.7. Mega-Constellations and Mega-Debris

Debris experts are worried about an increase in collisions because the number of spacecraft increase, thus creating even more debris. There is a symbolic depiction of debris around Earth shown in Fig. 2. Concerns about mega-constellations are not about the spacecraft only but rather about the potential for debris generation from the explosion or collisions involving a mega-constellation spacecraft [9, 10]. In any case, both debris experts and mega-constellation developers are aware of the additional risks that hundreds or thousands of new satellites could pose for a region of space where the amount of debris continues to grow even with

Figure 2 – Space debris growth

the current population of satellites. Debris is already a problem that is being faced actively with surveillance networks and avoidance maneuvers from the spacecraft operators. An Earth observation satellite may find unexpectedly another one in its field of view, or a region of space may become overcrowded and as a result impact the quality of space observations from ground. Making the spacecraft reenter at the end of its life and thus preventing it from becoming debris itself are also of great importance.

## 3. Spatial Grasp Technology

### 3.1. General Ideas

Within the Spatial Grasp Technology (SGT) [11–17], a high-level scenario for any task to be performed in a distributed world is represented as an active self-evolving pattern rather than a traditional program, sequential or parallel. This pattern, written in a high-level Spatial Grasp Language (SGL) and expressing top semantics of the problem that has to be solved, can be started from any point of the world. It then spatially propagates, replicates, modifies, covers and matches the distributed world in parallel wavelike mode, while echoing the reached control states and data found or obtained for making decisions at higher levels and further space navigation, as symbolically shown in Fig. 3.

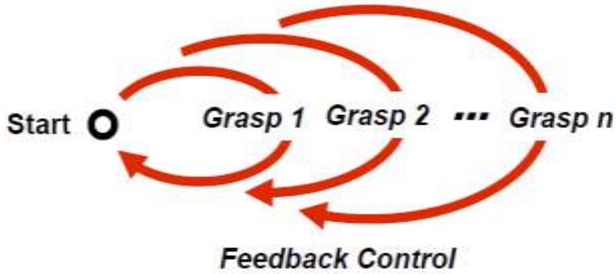


Figure 3 – Wavelike navigation, matching and grasping of distributed spaces

Within this inherently parallel and fully distributed spatial process the reached physical or virtual world points, whatever remote they happen to be, new spatial wave processes, which remain under control from the previous points or become independent from them, can be launched. Many spatial processes in SGL can start any time and in any places, cooperating or competing with each other, depending on applications. Self-spreading and self-matching SGL patterns-scenarios can create active spatial infrastructures matching any other systems and models.

### 3.2. The Worlds SGT Operates with

SGT allows to operate directly with the following world representations:

• *a Physical World* (PW) which is considered as a continuous and infinite world, where each point can be identified and accessed by physical coordinates expressed in a proper coordinate system (terrestrial or celestial) and with the given precision. PW can also include identifiable objects of any complexity associated with certain physical coordinates which may change in time because the objects can move in space. Any movements in PW and any operations on its objects are possible in SGT, with identifying its points, regions and objects by their physical coordinates;

• *a Virtual World* (VW) – a discrete world that consists of nodes and semantic links between them, with both nodes and links capable of containing arbitrary information of any nature and scope. VW nodes may have unique addresses reflecting their implementation details in networked environments by which they can be reached directly, unambiguously (as nodes may have repeating names) and in the quickest way;

• *an Executive world* (EW) consists of active «doers» with some communication possibilities between them. These may represent any devices or machinery capable of operating on the previous two worlds including properly equipped humans, robots, mainframes, laptops, smartphones, intelligent sensors, satellites, etc.

Different kinds of combination of these worlds can also be possible within the same formalism. These combinations can be:

• *a Virtual-Physical World* (VPW) where individually named VW nodes can be associated with some coordinates of certain PW points or any its regions, as well as with certain identifiable objects in PW with their respected coordinates;

• *a Virtual-Execution World* (VEW) where doer nodes may have special names assigned to them and semantic relations between them what makes it similar to pure VW nodes. Thus they can potentially become parts of arbitrary large semantic networks including different additional concepts and various relations between them;

• *an Execution-Physical World* (EPW) which can have doer nodes associated with certain PW coordinates which can be stationary or can change over time because doers can move in a physical space. Doer nodes may also correspond to certain objects in PW, treating them as programmable and active;

• a *Virtual-Execution-Physical World* (VEPW) which can combine all features of the mentioned above cases.

### 3.3. Spatial Grasp Language

General SGL organization is as follows: syntactic categories are shown in italics, vertical bar separates alternatives, the parts in braces indicate zero or more repetitions with a delimiter at the right if multiple, and constructs in brackets are optional:

***grasp*** → *constant* | *variable* | [ *rule* ] [({ ***grasp***,})].

An SGL scenario, called *grasp*, applied in some point of the distributed space, can be a *constant* or a *variable* with the content assigned to it previously when staying in this or other point of space (as variables may have non-local meaning and coverage). It can also be a *rule* (expressing certain action, control, description or context) accompanied by operands which can be of any nature and complexity, and embraced in parentheses. Rules, starting in some point of the world, can organize navigation of the world sequentially, in parallel or any combinations thereof. They can result in staying in the same application point or can cause movement to other world points with the obtained results to be left there, as in the final points of the rule. Such results can also be collected, processed and returned to the starting point of the rule. The final points of the world reached after the rule invocation can become starting ones for other rules. The rules, due to the language organization, can form arbitrary operational and control infrastructures expressing any sequential, parallel, hierarchical, centralized, localized, mixed and up to fully decentralized and distributed algorithms. In more details, the top level SGL organization may be summarized as follows. Full description of SGL can be found in [11–14].

***grasp*** → *constant* | *variable* | [*rule*] [({ ***grasp***,})]
*constant* → *information* | *matter* | *custom* | *special* | ***grasp***
*variable* → *global* | *heritable* | *frontal* | *nodal* | *environmental*
*rule* → *type* | *usage* | *movement* | *creation* | *echoing* |
*verification* | *assignment* | *advancement* | *branching* |
*transference* | *exchange* | *timing* | *qualifying* | ***grasp***

### 3.4. Networked SGL Interpretation

The dynamic network of SGL interpreters (details on their structure and organization can be found in [11–16]) covering distributed physical, virtual and execution spaces, may have any (including runtime changing) topology and operate without any central facilities or control, as shown in Fig. 4 (where SGL interpreters are depicted as universal processing and control modules U).

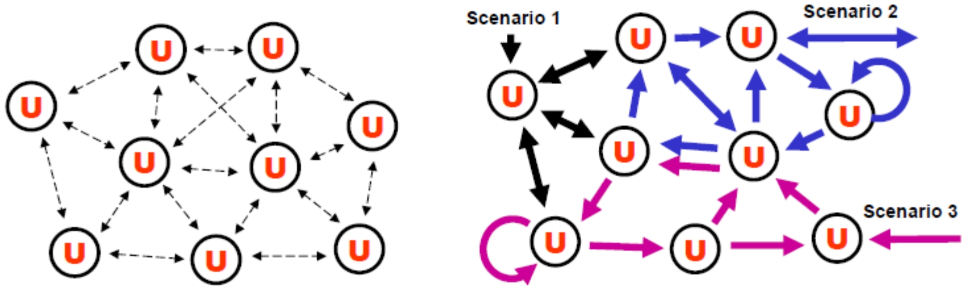


Figure 4 – SGT as a universal spatial computer: a) possible runtime communications between SGL interpreters; b) self-evolving competing or cooperating SGL scenarios

Any interpreter and groups of interpreters can simultaneously support and process multiple SGL scenarios which appears to be in their responsibility at different moments of time. Implanted into existing or planned distributed systems and integrated with them, the interpretation network (having potentially from a million to several billions of communicating interpreter copies) allows to form a spatial world computer with practically unlimited power for simulation and management of any terrestrial and celestial systems and problems.

### 4. Integration of Satellite Constellations under SGT

As was mentioned in Section 2, nowadays almost all communication with satellites and between them is accomplished via ground-based antennas and infrastructures, as shown in Fig. 5. These antennas are constructed with the aim of dealing with LEO satellites because they have to turn around and provide handover of loads between satellites which move fast around the globe.

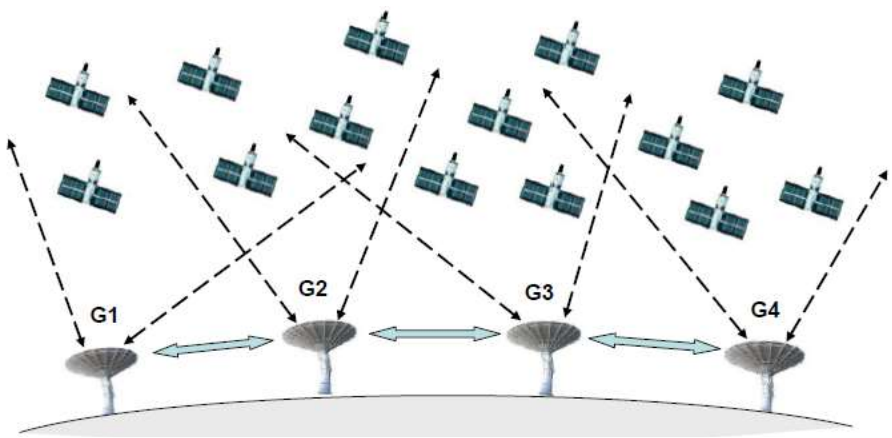


Figure 5 – Communication with satellites and between them via ground antennas and infrastructures

At the same time supplying satellites with SGL interpreters, which may communicate directly with each other as an integral system and also with the ground stations, may significantly simplify ground antennas and reduce their numbers, as shown in Fig. 6.

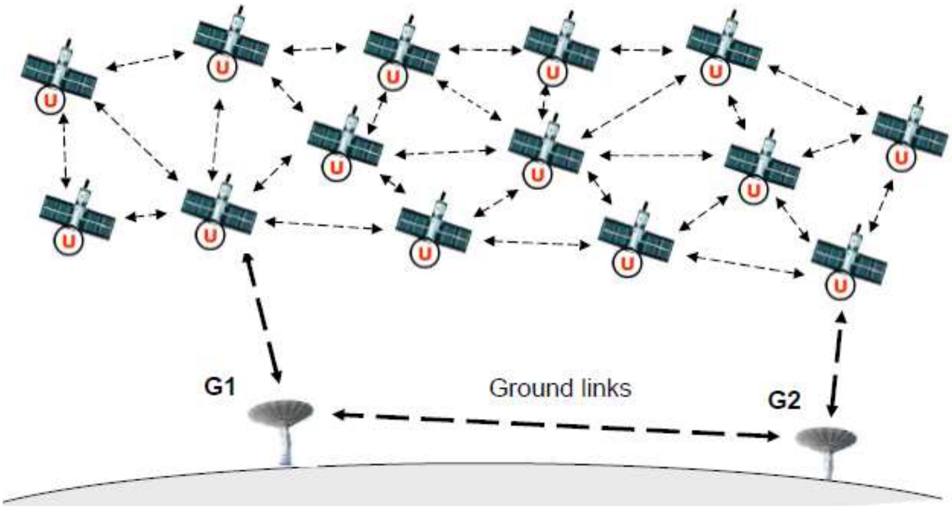


Figure 6 – Conversion of the constellation into an integral system under SGT
with simplification of ground infrastructures

There is only a snapshot shown in Fig. 6 because the position of satellites and communication structure between them may rapidly change over time.

## 5. Examples of Elementary Practical Solutions under SGT

### 5.1. Broadcasting Executive Orders to All Satellites via Direct Communication between Them

Fig. 7 represents the process of communication between satellites: starting from the first reached satellite from the ground station G1, orders are broadcast via the dynamic network to all other satellites, blocking possible cycling and delivering the given order for execution.

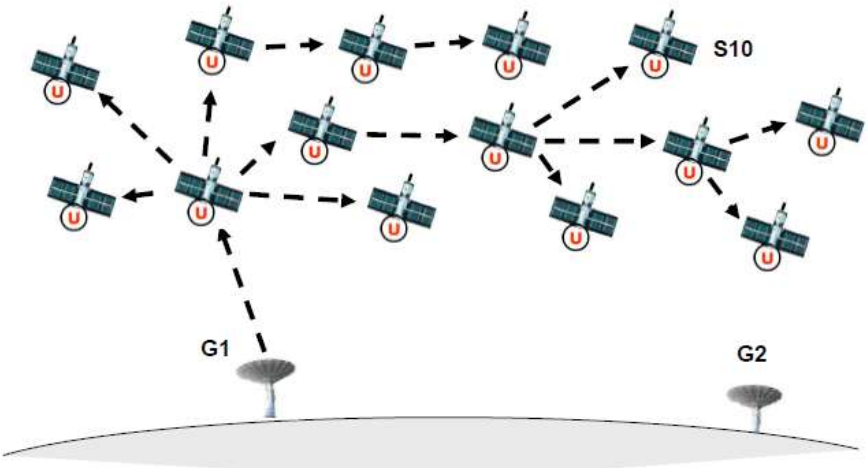


Figure 7 – Broadcasting executive orders via parallel network navigation in a flooding mode

Each reached satellite first executes the order brought to it in a frontal variable order and then spreads further the network coverage via neighboring nodes, as by the following SGL scenario.

```
frontal(Order) = instructions;
hop(G1); hop_first_any(seen);
repeat(execute(Order); hop_first_all(seen))
```

Executive orders brought to satellites can be also executed by them simultaneously with their directing to other satellites, thus covering the whole constellation with executive orders and carrying out their execution much quicker, as follows:

```
frontal(Order) = instructions;
hop(G1); hop_first_any(seen);
repeat(free(execute(Order)), hop_first_all(seen))
```

Sending the order to a particular satellite S10 via the dynamic constellation network, its execution and then aborting the whole remaining network navigation, can be expressed as follows (Fig. 7):

```
frontal(Order = instructions, Destination == S10);
hop(G1); hop_first_any(seen);
repeat(if(NAME == Destination, (execute(Order); abort),
          hop_first_all(seen)))
```

### 5.2. Broadcasting Orders to All Satellites, Collecting and Returning Their Accumulated Data

Broadcasting orders to all satellites via their dynamic network from the ground station G1, collecting the accumulated data (which is supposed to be in their personal nodal variables – History), returning them to G1 with their further transference to another ground station G2 and fixing there the final result (Fig. 8) may be achieved as follows:

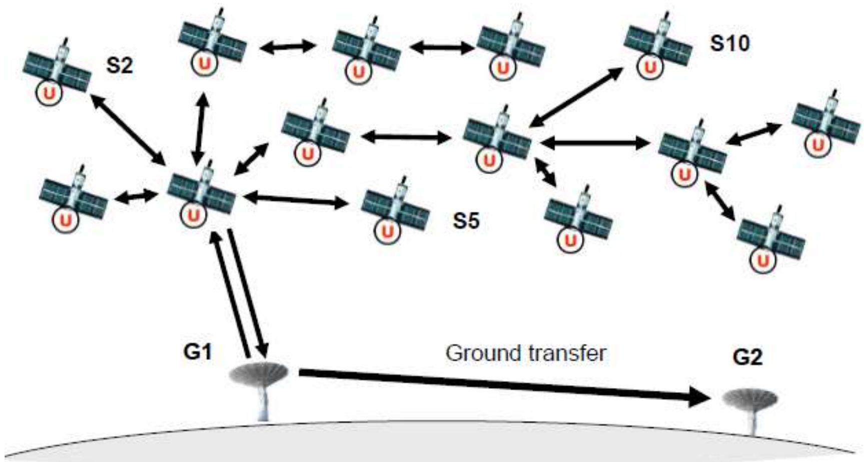


Figure 8 – Broadcasting orders to the whole constellation with the collection and returning of the data accumulated in all the satellites

```
hop(G1);
frontal(Summary) =
   (hop_first_any(seen);
    repeat(free(History), hop_first_all(seen)));
hop(G2); output(Summary)
```

If to collect histories from only particular satellite nodes (like S2, S5, S10), in SGL it can be written as follows (Fig. 8):

```
hop(G1);
frontal(Summary) =
```

```
   (hop_first_any(seen);
    repeat(if(belong(NAME, (S2, S5, S10)), free(History));
    hop_first_all(seen)));
hop(ground, G2); output(Summary)
```

Real implementation of this scenario may depend on the constellation dynamics and stability of their network topology where replying to the predecessor satellites with accumulated data may be complicated if their direct spatial links happen to be broken over time (e.g., when optical links are used). This may be done explicitly at the programming level for reaching a particular satellite via their current network topology (similar to what is described in Section 5.1) or at the interpreter implementation level, where return to the previous satellite address automatically involves its search via navigation through the dynamic network.

### 5.3. Constellation Repositioning and Restructuring

Any necessary constellation repositioning and restructuring, including emergency-like, can be done in a similar way, starting from any ground station and by the following SGL scenario as shown in Fig. 9. This restructuring may involve removal of used or malfunctioning satellites from the orbits (it is expected that it will not contribute to the rapidly growing huge collection of debris) and adding new satellites to the constellation (not included into the scenario) as well.

```
hop(G1);
frontal(Correction = advised, Removable = (S3, S6, S9));
hop(ground, G2); hop_first_any(seen);
repeat(
  free(update_position(History, Correction);
       if(belong(NAME, Removable), remove(current))),
  hop_first_all(seen))
```

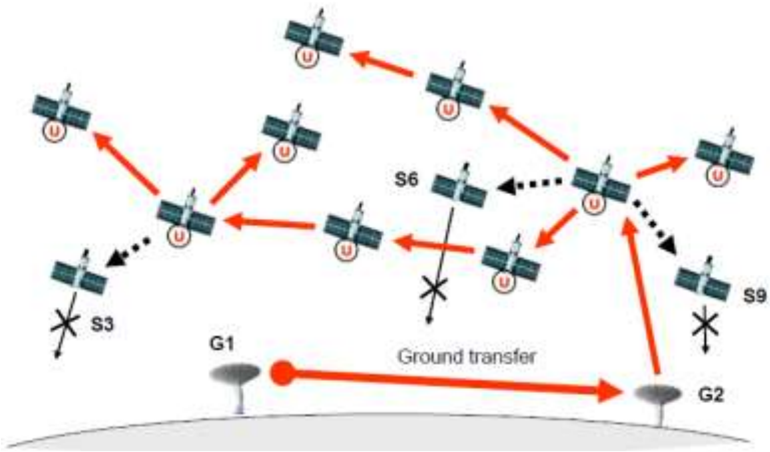


Figure 9 – Constellation repositioning and restructuring with removal of used satellites

### 6. More Complex Constellation Solutions under SGT

In the previous section only some basic operations on distributed satellite constellations, which can be organized as a whole by using the developed networking technology based on self-spreading and self-matching high-level recursive and parallel scenarios, were considered. In the recent paper [18] some more specific operations on satellite networks under SGT, which may be useful for such important applications as global security and defense, were shown. These operations included the effective use of organized satellite networks for tracking rapidly and complexly moving objects like hypersonic gliders, constant observation of important objects on Earth in a custody-like manner with low-flying LEO satellites, which themselves rapidly move around the globe and can be seen over its points for only a few minutes. It was also shown that by operating SGT in the same formalism with physical, virtual and executive worlds, as well as with their combinations (as it was mentioned in subsection 3.2), the capabilities of satellite constellations can be essentially improved through the introduction of a virtual layer over satellite networks, which enables, for example, uninterrupted observation of any large infrastructures on Earth, and not only local points or objects. In a new book that is currently being prepared (its extended draft contents can be found in [19]), more operations on satellite constellations and mega-constellations will be presented. The recent paper [20] described the use of SGT for dealing with global terrestrial and celestial networks where parallel spatial methods over large networks can be also useful for mega-constellations of satellites and their integration with ground-based networks and systems.

## 7. Conclusions

Possible application of the developed Spatial Grasp Technology for effective management of large constellations of predominantly LEO satellites based on parallel recursive navigation and matching of large distributed systems capable of changing their scope, communication possibilities and networking topologies during their runtime, thus reflecting the expected features of numerous space-based objects and their groupings, were described. Based on the experience with implementation of previous SGT versions in different countries, the developed approach allows to make efficient implementation even within standard university environments and, if necessary, with the help of the author of this paper. High-level recursive scenarios in SGL are often much more compact and simple than other approaches and languages which may also be important for optimizing and reducing communication load between satellites and the interference with other space communications. The future plans of this approach in relation to space-based systems, as was mentioned in the previous section, include the new book currently being prepared which will consider the use of SGT in a broader scale for the conquest of space up to cislunar regions and beyond, as well as integration of satellites (from LEO to GEO) in different orbits.

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