RESEARCH ARTICLE

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Advanced Applications of Swarm Robots in Astronomy, Specifically in Outer Space and on Celestial Objects

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Abstract

Swarm robots are simple physical robots that work collectively, coordinating and communicating amongst each other resulting in intelligence and computational power far more than the capacity of a single robot amongst them; to do complex, big, time-consuming, and sophisticated tasks. These are simple, strong, robust, less prone to damage, inexpensive, easily producible, and fast; therefore, they are perfect for astronomical uses, especially in outer space and on celestial objects. The main basic focus of our paper is the applications of swarm robotics in Astronomy, specifically in space. To cover all the applications and not leave anything behind, we have developed a hierarchical system, named by us as Pingakshak's system, and have divided the applications in groups such that even if there are applications beyond our present time's technology, the system, can still be useful, and the system developed is also flexible, i.e., more groups and applications can be added later. We then also have reviewed eleven research papers, two theses, and one book to give an idea about the amount of research that is being carried out in this field. We then have identified all the grey areas in the result section, pointing towards all the applications with very little and incomplete research and informing other researchers about the incompleteness in the field of swarm robotics.

Keywords: Applications, Ascending order, Swarm intelligence, Swarm robots.

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Introduction

Groups of robots that could work like cells of an organism to assemble more complex parts and possesses some special characteristics, which in fact are found in swarms of insects, i.e., decentralized control, lack of synchronicity, simple and (quasi) identical members with size not as large as to be dealt with statistical averages, not as small as to be dealt with as a few-body problem, i.e., in order of 102 – 10<<23, are called as swarm robots, earlier known as cellular robots. And the concept of intelligence in relation to cellular robots is known as "swarm intelligence".[1] And swarm robotics is the study of how to design groups of robots that operate without relying on any external infrastructure or on any form of centralized control.[2,3]

In 1988 the term swarm in the context of robotics was applied by G. Beni. One year later, G. Beni and J. Wang introduced the concept of swarm intelligence. In 1993, C. Ronald Kube and Hong Zohng constructed a multi-robot system inspired by the collective behaviors of natural swarms. In the same year, Gregory Dudek et al. define swarm robotics with respect to different features, including the size of a swarm, communication range amongst the robots in a swarm, communication topology, communication bandwidth, reorganization rate of a swarm, abilities of swarm members and swarm homo- or heterogeneity. After this, there was not much significant development in this field. However, in 2004 G. Beni made another attempt to describe a swarm more precisely.[4]

Current research is focused on the design analysis of controlling algorithms and collective behavior (strategies) of swarm robots.[3] But there is also research on the development of algorithms, controlling systems, communication systems, etc.

There are a lot of benefits of swarm robots few of them are mentioned below:[4]

- Robots are autonomous that can cope with their environmental changes.

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- Robots can combine their powers and abilities to form complex structures and offer unlimited features.
- The systems are flexible. That means they can be applied in different fields and for a variety of tasks.
- The systems are scalable, which means all robots can manage to obtain their goals no matter how big or small the swarm is.
- Parallelism makes the systems work faster. Parallelism means tasks can be divided into sub-tasks that can be allocated to different robots.
- Robots are designed very simply, which means they are also cost-effective.[4]

Few basic tasks that, along with many others that are covered our in the system, are:[2]

- Tasks That Are Too Dangerous
- Tasks That Scale-Up or Scale-Down in Time
- Tasks That Cover a Region
- Tasks That Require Redundancy[2]

All of their capabilities are mentioned below in the form of their applications.

Applications

The following are the applications divided and subdivided hierarchically in three layers grouping them together based on their similar characteristics, and the size of groups decreases further down the hierarchy and vice versa.

Basic Applications

The following are the basic/ first hierarchical group of applications of swarm robotics in space. These are the five major groups covering all the applications of swarm robotics in space. All of them are explained in short below Figure 1.

Exploration

The first basic and major step needed in astronomy for greater knowledge, understanding, and field of livability is exploration. As, before humans can go to any destination in space, we need to have all knowledge related to that destination, and sending single robot missions is very expensive and cannot cover a lot of area in a short time, and because of this, a lot of information cannot be obtained from them, so they are inefficient. But a swarm of small robots can do so effectively in a short time and are inexpensive. [Best for exploration] [Figure 2].

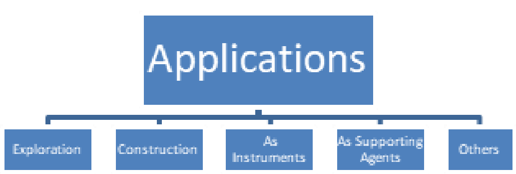

Figure 1: Flow chart for Major applications.

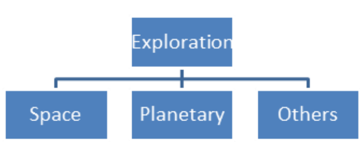

Figure 2: Flow chart for applications of section exploration.

Space Exploration

Exploring space is not much of a concern for us now as currently, wherever we go, we can see it through our telescopes, but in the future, when we will become a type two or greater type of civilization, we will need these swarms of robots to explore not only space but they can also be used in search and rescue of our broken space crafts and any human space ships.

Planetary Exploration

Exploring a planet for colonization and resources are amongst the basic applications; this may include- exploring lava tubes, caves, craters, good landing spots, etc. Within which a single robot could get lost or would take a lot of time to do so, a swarm of robots could do it in very less time and resources.

Others Parts

This includes all other celestial objects such as asteroids, comets, moons, etc., which single big satellites or rovers cannot do an elective job. And this section is also kept for future expansion.

Construction

Once the exploration and analysis of observed data are done, our next stage is to construct/build the required infrastructure for further exploration or colonization in space or the aimed destination [Figure 3].

Orbital Construction

Construction of infrastructure such as space telescopes, space stations, orbital depos or space elevator, etc., are few structures that is to be built in orbits of planet or moons for further development of our knowledge or colony.

Extraterrestrial (Planetary) Construction

Building infrastructure like planetary crater telescopes, habitat for scientists, or even colonizing an entire planet helps humans to grow and develop as a species.

Servicing and Maintenance

This includes servicing and maintenance of the structures constructed in both orbits as well as on celestial objects.

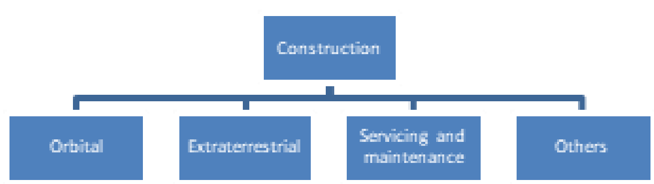

Figure 3: Flow chart for applications of section construction.

Other Places

This is not constructed around a normal celestial object like a planet or moon; this is constructed at lagarian points or around the Sun. And this section is also kept for future expansion.

As Instruments

Swarm robots are not just good in-field tasks. They can also be used within a working machine, instrument or infrastructure [Figure 4].

Controlling

Swarm robots can be used to the paraments or parts of other devices such as small mirrors in a telescope or physical dimensions [width, length, etc.] of the area set for research, or swarm intelligence [software] can be used to control a large number of other machines which are not small or even may not be robots, etc.

Computing

A complicated single computer is very expensive, delicate, and prone to damage, but a large amount of small not so complicated computers are very effective and can overcome all the difficulties and risks related to space travel.

Networking

In space or other planets where a huge tower system cannot be developed, swarm robots can serve as a great mobile alternative supplying energy [electricity], or helping in communications, etc.

Measuring and Scientific Studies

This may include all the activities that we need to measure certain parameters such as ionization of the upper atmosphere, magnetic strength of some celestial body, gravitational waves, etc. This section may also include the use of swarm robotics to demonstrate the state of the art technology in space and study their functioning in the actual working environment.

Separate Missions

Swarm robots can be used to do separate missions without exploration and construction. They may include all the essential applications that a presently a single robot/satellite is doing like mining, search and rescue, etc.

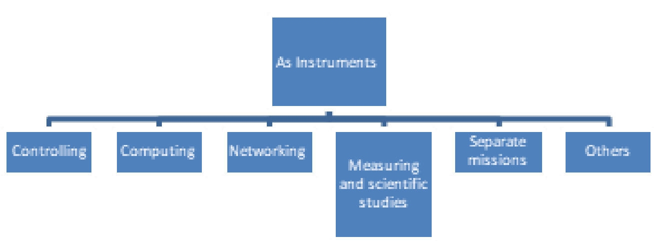

Figure 4: Flow chart for applications of section as instruments.

Others

This section may include very small and unnoticed, unnecessary applications, but very important ones could be hidden and kept for future expansion.

As Supporting Agents

This section could have been merged into other sections. Still, these applications are very important, so they needed special attention as the major work of automation is to assist humans and collectively do work for humans without needing special attention [Figure 5].

Gathering Materials

This section covers all the applications such as gathering materials for building infrastructure, gathering minerals, and other resources. This even includes gathering materials for recycling or reusing in orbit, celestial objects, or anywhere else.

Gathering Energy

This section focuses on gathering and supplying energy for other robots to perform so may it be the planet's geothermal energy or solar energy using solar panels or through Dyson's swarm.

Part of Something Else

Swarm robots can be used as a functioning part of some bigger mechanism or machine as a support system like to be used as small mirrors of big space telescopes, or as nanosatellites and work as part of big structures, etc.

Imaging

This could include telescopic uses, observation of celestial objects up close or Earth from orbit, etc.

Others

This section may include applications such as pulling asteroids in Moon's or Earth's orbit and mining for resources, etc.

Others

All the above sections cover major application areas, but this section is kept to cover all the earth-related applications such as household automation, weather monitoring, etc.; but as this is not our subject of interest, this is kept for future studies for other researchers. All the basic applications even in this section are the same as above but related to Earth, so the

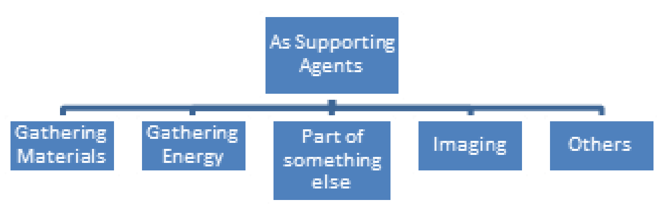

Figure 5: Flow chart for applications of section as supporting agents.

Table 1: Review table for already studie d applications of swarm robots in space.

Investigation carried out and summary	Application covered
1. Experimenting with the applicability of swarm robotics in finding caves on other planets using a computer simulation, with the strategy of using bee behavior as the basis of robot programming and robot controls, running many simulations comparing a number of robots to the total number of caves found, the time it took to find first cave, hits on best caves [first, second, third], Number of Hits on Cave in 10 sols, Average Number of Caves Found in 10 sols, the total number of hits, average distance covered, Average Time to Find First Cave (sols) and also compared every result with the existing parameter if any and found out the errors.[5]	Using swarm robots to explore other [than Earth] planetary caves [here with an example of Mars], which are potential sites where human colonies could be built.[5]
2. This paper describes the PAM [Prospecting ANTS Mission] mission of NASA's HEDS [Human Exploration and Development of Space] enterprise within which they describe how the prospecting of the main belt will be done, ANTS [The Autonomous Nano-Technology Swarm] with the strategy of the ants themselves [hierarchical distribution with several levels], autonomous formation flying in deep space by the robots [Transfer from Earth's Lagrange Point to the Main Belt, Operations in the Main Belt: Infrastructure, Teams, and the Unknown], considerations of asteroid science, instrumentation, and optimal operations, drive requirements for formation flying technology and, more broadly, cooperation, and the importance of fully autonomous operations in very uncertain environments is discussed.[6]	Using swarm robots [here, spacecrafts] for exploring and studying the objects [asteroids] in the asteroid belt for their resource potential and revealing our solar system's past and formation history.[6]
3. This is a review paper, in which a survey of 39 multi-satellite missions in various stages of development is carried out, where each satellite's mass is less than 10 kg and are categorized based on their mission type and status, number of satellites, lead institution, and funding source.[7]	This paper covers specific concentrated applications of nanosatellites: A. Earth science missions: develop a scientific understanding of the Earth system and its response to natural and human-induced changes to enable improved prediction of climate, weather, and natural hazards for present and future generations- 1. measure ionospheric in situ plasma densities, measure DC and AC magnetic fields in situ, which facilitated accurate identification of geospace storm-time features like the geomagnetic-storm-enhanced density bulge and plume 2. assess the spatial scale and spatial-temporal ambiguity of magnetospheric microbursts in the Van Allen radiation belts 3. provide high-resolution images of Earth for environmental, humanitarian, and business applications [constellation satellites] 4. Demonstrate the capability of launching and deploying a fleet of satellites [eight here] into an uncontrolled constellation approximately 500 km above Earth. It is to characterize the radiation environment in LEO by measuring the location and intensity of energetic charged particles simultaneously over a geographically dispersed area. [Testing and measuring purpose]. 5. Used to perform multipoint, in situ measurements in the lower thermosphere (90–350 km) and re-entry research. 6. Ionospheric remote sensing [space weather measurement] 7. Observe the spatial and temporal variations in the ionosphere and aurora by conducting in situ observation. 8. Obtain high spatial, high temporal resolution multispectral images of coastal and inland waterways. This information is necessary for understanding the evolution of ecological systems and sediment suspension in river estuaries, the effects of anthropogenic processes on water systems, and the effects of tidal forcing on ocean color. 9. Perform in situ measurements to understand geomagnetic storm generation in the magnetosphere, especially in the magnetotail region, where these storms start.

Investigation carried out and summary	Application covered
	10. Image the key geophysical parameters that are needed to improve the prediction of extreme weather events. 11. Measuring the bidirectional reflectance distribution function of the Earth's surface (i.e., the directional and spectral variation of reflectance of the surface). 12. Measure the global wind field for compiling vertical profiles of the wind field and for long-term weather forecasts. 13. Ionospheric tomography [understand the ionospheric response to solar, magnetospheric, and upper atmospheric forcing and perform tomographic measurements of ionospheric density]. 14. Search for space debris in the medium Earth orbit and geostationary Earth orbit (GEO) belts. 15. Earth observations and monitoring Earth's local space environment [lunar constellation: providing telecommunications links, mapping the Lunar surface, and supporting future missions on the moon]. B. Astronomy and astrophysics missions: understand the universe and our place in it-- 16. Provide milli-magnitude (0.1% error) differential photometry of bright stars [six nanosatellites using Generic Nanosatellite Bus platform]. 17. Autonomous assembly and reconfiguration of a space telescope. 18. Radio astronomy in the operational band of 0.3–30 MHz. 19. Observing space in the 1–100 MHz frequency range at one of the Sun-Earth Lagrange points. C. Planetary science missions: understand the planets and small bodies that inhabit our solar system and the origins of life-- 20. Evaluate communication, navigation, and payload-hosting technologies beyond Earth orbit. 21. Study the frequency, geographical distribution, and severity of electrical activity on Mars. 22. Measure the temperature, pressure, and electron density profiles of a planet's atmosphere and ionosphere. D. Heliophysics missions: explore the sun-Earth system to understand the Sun and its interactions with Earth and the solar system-- 23. Studying helioseismology and magnetic fields of polar regions. E. Technology demonstration missions: demonstrate the application of state-of-the-art technology in space.[7]
4. This paper aims to study the application of swarm robots in interstellar space exploration by explaining the interstellar space exploration concept, taking some existing non-swarm examples, developing and explaining the resilience principles and swarm architectures, and doing so system and strategy analysis [More theory fewer applications].[8]	Using swarm robots for interstellar space exploration.[8]
5. This paper reviews some of the various worldwide projects to develop and apply innovative swarm-type robots to many challenging applications and gives a review about the commercialization of swarm robots taking an example Kilobot swarm-type robot and also explains some other applicable swam robots.[9]	Applications explained here [which are in our context]: 1. Swarm robots can self-assemble devices in space, as well as provide swarm intelligence such as pattern recognition, sensor-based motion, and adaptive shape change 2. TERMES robot is a swarm program inspired by studying termite mounds: build towers, castles, and pyramids while autonomously building stairs to reach high levels and adding bricks where needed—these can be used to build an extraterrestrial colony. 3. Swarming Micro Air Vehicle Network (SMAVNET), which can be used to rapidly create a communications network another type of swarm robot can be deployed one at a time, they hold positions, and the remaining robots move ahead to complete the communication network. 4. SWARMONOID Project 11084 to develop a trio of swarm robots, a Foot-Bot, a Hand-Bots, and Eye-Bots, which can be used in extraterrestrial colonization and is one unit for all functions.[9]

Investigation carried out and summary	Application covered
6. This paper compares mechanisms in ANTS systems to their biological analogs, their requirements, optimal applications, strengths, and weaknesses.[10]	The applications covered: 1. Solar sail deployment 2. Planetary surface mobility 3. Lander positioning/support[10]
7. This paper is a complete guide for Micro Autonomous Positioning System [MAPS] for telescopes for Pick-off mirrors [POMs] using various swarm robots such as ANTS, etc. This paper completely covers the specifications required, various designs and parameters, power systems, assembly, test-test results, and future work/scope.[11]	Using swarm robots in ground-based telescopes within its focal plane for just picking the light from the objects of interest and eliminating the space with it, which conventional single mirror telescopes are incapable of.[11]
8. This paper presents an operating concept for radio interferometers called the swarm telescope concept based on its resemblance to the idea of swarm intelligence, taking the example of LWA stations and also explains the specific case of ngVLA about the advantages [reduced operations costs for the array, improved responsiveness to targets of opportunity, etc] it has been using this concept.[12]	Using swarm intelligence [completely software-based, nothing about the telescopes themselves] in the modern new telescopic observatories for simplicity, cost-effectiveness, energy-saving, and much more advantages.[12]
9. This paper explains, examines, and analyses in detail swarm satellites, SWIFT [Swarms of Silicon Wafer Integrated Femtosatellites] swarm system, dynamics and control of swarms of Femto satellite, and sparse aperture application and performance-cost analysis; covering everything to make SWIFT project a reality.[13]	Using swarms of spacecraft is sparse aperture sensing or stellar interferometry [creating aperture (mirror) to be used as a telescope in LEO].[13]
10. This is a review paper that relate multi-robot research with a focus on space applications and starts by examining definitions of, and some of the fields of research, in multi-robot systems and also gives an overview of space applications with multiple robots and cooperating multiple robots; the multi-robot cooperation techniques used in theoretical research, as well as experiments, are reviewed, and the applicability for space applications is investigated.[14]	Uses covered: [1] Planned Missions and Visions: A. In-Orbit Operation and Satellite Formations: 1. Multiple light-weight rovers to explore Mars 2. In-Orbit Operation and Satellite Formations 3. On-Orbit Servicing (OOS) 4. For using fuel from damaged, overloaded satellites as well as their fail-safe fuel at EOL and store the fuel on-orbit and use it to service other satellites. 5. Guidance and navigation and the capturing mechanism for non-cooperative and cooperative client satellites will perform orbital maneuvres that can be used to de-orbit old or damaged/non-functioning satellites. 6. Micro-satellite formations to enable unlimited (virtual) aperture sizes, more straightforward system upgrade, and low-cost mass production 7. Land multiple probes on Mars to analyze the Martian atmosphere. [i.e., widespread sensor network and no actuators] 8. Detect and observe gravitational waves from astronomical sources 9. Build space structures [assembly, inspection, and maintenance] B. Surface & Planetary Exploration: 10. Using space exploration for R&D working in hostile and dangerous areas and acting in place of humans to perform assembly, maintenance, and production tasks. 11. Used for mining of moons and asteroids, the construction of habitats [planetary], the detection of valuable resources (example, water or oxygen), and astronaut support during manned missions [2] Implemented Space Applications: 12. Automatic Rendezvous and Docking 13. Formation Flying [low resolution, high coverage sensors to trigger observations by high-resolution instruments, study the effects of the solar wind around Earth in three dimensions and time-varying phenomena in the magnetosphere, measure the geomagnetic field in 3D, 3D image generation of the Earth's magnetosphere and provide near-simultaneous observations and continues

Investigation carried out and summary	Application covered
	study of aerosol distribution, cloud layering, temperature, relative humidity, distribution of green-house gases and radiative fluxes (allowing better climate predications)] 14. Rovers [Mars Exploration][14]
11. This paper is a survey of existing concepts for in-space assembly of telescopes and introduces PULSAR (Prototype of an Ultra Large Structure Assembly Robot), the latest European effort toward proving the feasibility of the technologies required for autonomous robotic assembly of a telescope or a large space-borne structure.[15]	Using swarm robots for assembly in the space of a large telescope [other thing mentioned is that satellites flying in a precise formation can mimic the behavior of a rigid structure, even without physical docking, solar arrays for power plants, light sails to reach outermost regions of the solar system, and heat shields to land on Mars] taking an example of PULSAR.[15]
12. This thesis reports on the development and evolution of a micro autonomous pick-off mirror called the Micro Autonomous Positioning System (MAPS) that can be used in a multi-object spectrograph.[16]	Using swarm robots in precision and accurate control, coordination and positioning, and orbit maintenance of self-adjusting mirror of a space telescope, using them as instruments of control.[16]
13. This book is a brief overview of multi-agent systems and swarms robotics in space, especially at JPL, swarm guidance using Probabilistic Swarm Guidance using Inhomogeneous Markov Chains (PSG-IMC) Algorithm and it application to Mars and motion planning in cluttered environments using Spherical Expansion and Sequential Convex Programming (SE-SCP) Algorithm.[17]	A. Networked Planetary Exploration Teams for resources. 1. MOSAIC: Mars On-Site Shared Analytics Information and Computing to enable distributed and load-balanced high-performance computing across a Mars network B. Distributed Apertures 2. Distributed Swarm Antenna Arrays for Deep Space Applications C. Spacecraft Constellations and Convoys 3. Integrated Communication and Controls for real-time monitoring of time-varying or geographically distributed phenomena D. Multi-robot Construction Teams 4. Lunar Crater Radio Telescope construction.[17]
14. This book is a complete studied, analyzed, and developed work on space telescope architecture specifically concentrated on TITANS AE model and also has its validation against HST and JWST.[18]	Use of swarm robotics in controlling the space telescope's mirror and also in segmentation, modularity, assembly, autonomy, and servicing of the entire telescopes. [Used as instruments][18,19]

developed system with just a few changes can be further extended for Earth.

The following are the applications divided and subdivided hierarchically into three layers grouping them together based on their similar characteristics, and the size of groups decreases further down the hierarchy and vice versa.

Review Paper

Literature that we were able to find related to our topic is given in Table 1.

Results

As of now, we have seen all the areas, sections, and groups of applications of swarm robots in astronomy; here, we present all the grey areas within which research and development are needed for swarm robotics to be more applicable in astronomy.

As there are five major sections, their ranking according to research in ascending order is [Table 1][Figure 6]:

- Exploration
- As Supporting Agents
- Construction
- As Instruments
- Others

The ranking of subgroups within the sections in ascending order is as follows [Table 1]:

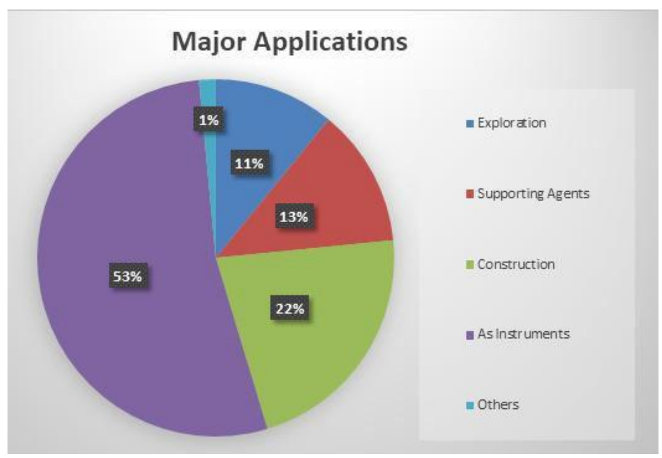

Figure 6: Percentage of research done in major application sections.

- Exploration: Others, Space exploration, Planetary exploring [Figure 7].
- As Supporting agents: Gathering energy, Others, Gathering material-imaging, Part of something else [Figure 8].
- Construction: Others, Servicing and Maintenance, Extraterrestrial Construction, Orbital construction [Figure 9].
- As Instruments: Others, Computing-separate missions, Networking, Controlling, Measuring and Scientific studies [Figure 10].

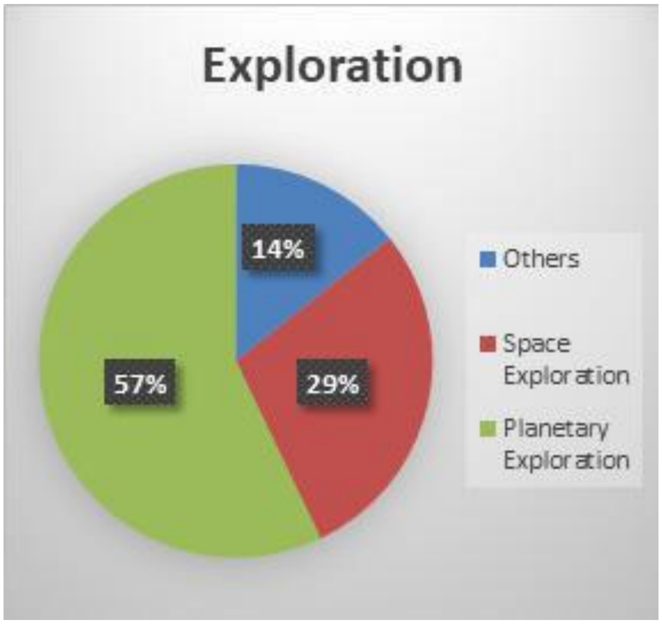

Figure 7: Percentage of research done in exploration section.

Figure8: Percentage of research done in As Supporting Agents section.

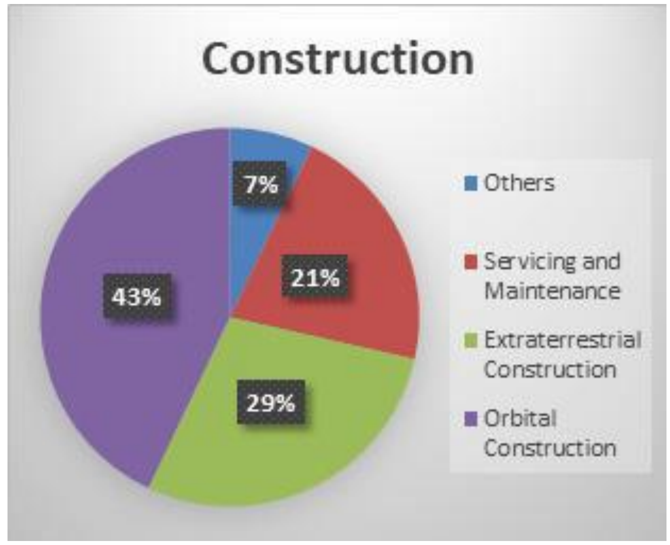

Figure 9: Percentage of research done in Construction section.

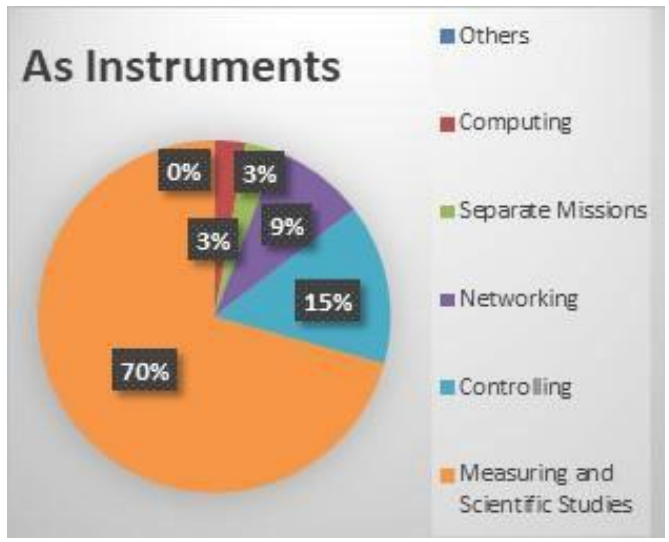

Figure10: Percentage of research done in As Instruments section.

All the applications and groups mentioned above have very high research potential, so a grey area was not identified typically as usual, but instead, we have ranked our findings in ascending order of the amount of research that is being carried out in it. This whole topic has very little research in it compared to the possibilities of its applications. The plotting below could help us understand which areas have been researched earlier and which are not even touched.

Conclus ions

Swarm robotics is a very deep, wide, and huge concept that cannot be covered in one paper, but we have tried our best to summarize all that there is about swarm robotics and given a great idea about future works and the scope of swarm robotics and swarm intelligence. We have summarized the concept of swarm robotics, given the available literature within the applications domain of swarm robotics, and have identified the grey areas for future research. This paper may help the development of swarm robots as these are the best type of known automation for future space applications overcoming all the challenges, related risks, and drawbacks of conventional systems. I would like to thank my guides as well as my co-authors, Sushrut Raijade and Suraj Panngarkar, for supporting me and guiding me through this research and making of this paper.

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I would like to give my special condolences to my mother and younger brother for their great contribution towards supporting and encouraging me.

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