Essential Technologies and Concepts for Massive Space Exploration: Challenges and Opportunities

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The space industry is growing at a tremendous pace generating attraction both from the industry and academia. Various governmental and industrial institutions are embarking on new programs aiming for more exploration of the industry. The impact of recent advances in the control system, computational technology, networking, Internet of Things (IoT), robotics, manufacturing, and machine learning (ML)/artificial intelligence could further support the space industry by providing the possibility of detailed and mass exploration of the deeper space. In that regard, this article reviews this multidiscipline area from the space exploration perspectives. This article focus on the most recent advancement in the aforementioned technologies along with control system theory considering the impact of long-distance between the controlling station and the intended site of exploration. We also provided a case-study analysis for the Martian surface while identifying technical and research challenges.

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I. INTRODUCTION

It is an inherent nature of humans to pursue discovery, observation, and exploration of our surroundings. We ask fundamental questions, such as where are we? Where do we come from? Is there a beginning and ending to human beings or the physical environment we are living in? What is in the beginning, what will be the next or the end if there be? As a part of such quests, a concrete step for human discovery and space exploration embarked in 1957, while the Union of Soviet Socialist Republics set in-motion Sputnik. Sputnik is the first man-made satellite placed in orbit around the Earth by humans. Since then there have been numerous satellites launched in the vicinity of the Earth as well as into deep space. Moreover, several space programs have been started and successfully completed and there are also numerous ongoing projects [1], [2]. Following the launching of the Sputnik, the National Aeronautics and Space Administration (NASA) began its operation on October 1, 1958 [3]. Since then space race between east and west has seen tremendous progress in space exploration and discovery. On December 6, 1958, the first U.S. satellite named Pioneer 3 was launched to ascend to an altitude of 63 580 miles. As much as the progress made during the U.S. versus Soviet space race with many significant accomplishments, there are also some deadly disasters that have deterred and devastated the space exploration community. The first catastrophic incident happened with Apollo 1—1967, in the course of preparations of the first crewed mission of the Apollo Space Program [4]. Since then there have been ups and downs in the industry.

Recently, reviving interest in space exploration has led to a huge surge in space programs, both governmental and commercial. Traditional space programs are usually run by government agencies. Currently, there are dozens of commercial space programs such as SpaceX, and Boeing. On November 15, 2020, SpaceX the first operational mission in the program launched. Whereas Boeing's first mission is expected to launch this year. Moreover, space programs' contribution to the global economy is also increasing. The global space economy in 2019 was \$423.8 billion, which has increased by 2.2% from 2018 and 73% for that decade. Fig. 1 depicted the growth of space industry within the last 10 years. An annual report from the Space Foundation records the private sector and consumers worldwide spending by governments. As per the report, the \$423.8 billion space economy is consists of commercial infrastructure and support industries, 28% and commercial space products and services, 51.3% [1]. As presented in Fig. 2, commercial space products and services takes more than half of the economic contribution of the space industry followed by the commercial infrastructure and support industries.

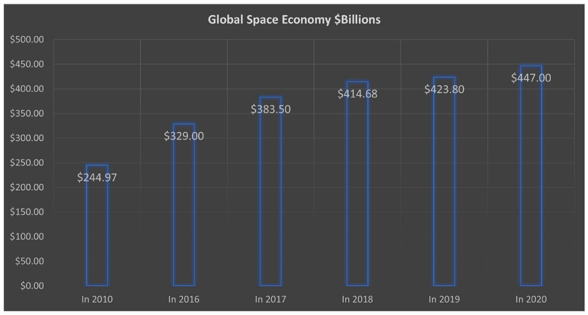

Fig. 1. Global space economy in the last decade [1].

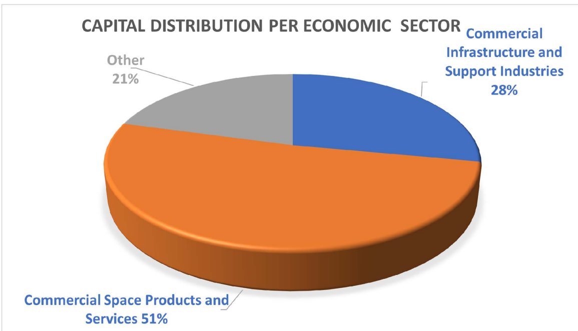

Fig. 2. Capital investment distribution per economic sector [1].

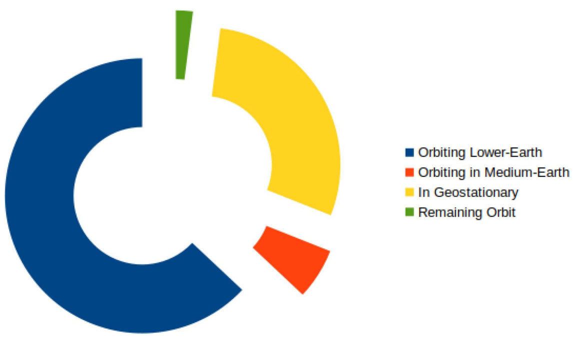

Fig. 3. Satellites launched to the vicinity of the Earth [5].

Various programs target various areas of the space. The most common programs focus on sending satellites to the vicinity of the Earth for various purposes such as Earth observation, reconnaissance, to act as a communication relay. These kinds of programs launched satellites to revolve around the Earth. Out of the total launched so far out of the total existing satellites, almost 63% orbit lower Earth, 6% are orbiting in medium-Earth, 29% are in geostationary, and the remaining 2% orbits in numerous elliptical shaped vicinity of Earth [5], which is depicted in Fig. 3. In terms of countries with the number of satellites launched, Fig. 4 shows the USA lead with 859 satellites, China follows in second with 250, and with 146 satellites, Russia is in third [5]. The most common and frequent human travels are to the international space station (ISS). It is the largest system ever assembled by humans in space.

Humans have also traveled to the Moon when Niels Armstrong landed on the surface of the Moon. Other programs have targeted other plants, including Mercury, Venus, Mars, etc., including the planets Moons [6]. The furthest

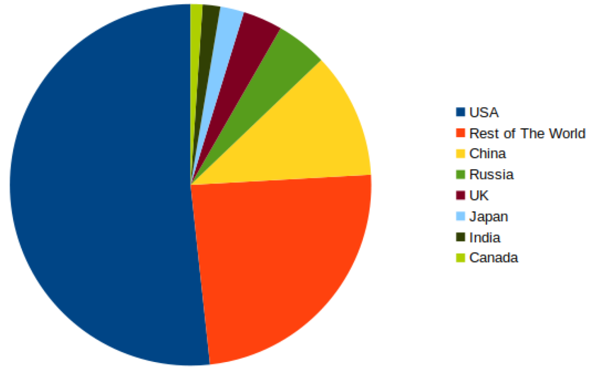

Fig. 4. Countries with the number of satellites launched [5].

a spaceflight was sent is the Voyagers 1 and 2. They are predicted to have sufficient electrical power and thruster fuel to continue their current suite of science instruments on until at least 2025. When, Voyager 2 is 18.4 billion km from the Sun and then Voyager 1 is about 22.1 billion km [7].

Most recently, NASA the leading institute in space exploration embarked on the Artemis [8] program, which is aimed at landing the man and the woman on the Moon by 2024. This will embark a new pioneering technologies in investigating much of the lunar surface than ever. By the end of the decade, the collaboration with commercial and international partners will create sustainable discoveries [8]. The program is also to learn what is on and around the Moon in taking the next massive step, which is to send humans to Mars.

Exploration of the Moon, Mars, and other deep space elements has been desired for a long time in human history. Since then, significant progress had been done on the technological front. However, human has never traveled beyond the Moon, even we have not been able to go back to the Moon since its first landing. Space travel has only happened in Earth's orbit, ISS.

Therefore, in the next decade, the explosion of the Moon and Mars exploration is expected. We are already witnessing the sign with the recent Chines Chang'e 5 spacecraft, which had successfully landed on the Moon and brought soil. The program was designed as an experimental for the return to lunar spacecraft. On December 1, 2020, Chang'e 5 landed in the vicinity of Mons Rümker on the Moon, which was launched in November 2020. It come back with two kg of lunar soil on December 16, 2020 [9]. Moreover, as a part of the Tianwen-1 mission, China's first interplanetary venture enabled a successful landing of Mars rover called "Zhurong" Red Planet [10]. Furthermore, European Space Agency also planned to send spacecraft to Mars for 2020. The program is called N$^{\circ}$ 6–2020: ExoMars, which is postponed to take off for the Red Planet in 2022 [11].

From a communication and network coverage perspective, the most notable advancement is the recent mission by Nokia and NASA to deploy the LTE access on the Moon. 4G is expected to transform lunar surface communication access. It is aimed at providing reliable, high-data rates while optimizing the power consumption, cost, and size. Wireless communications are a vital part of NASA's

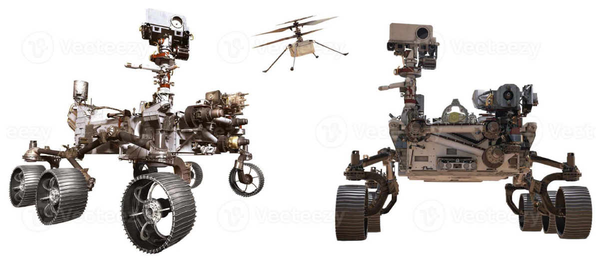

Fig. 5. Curiosity and Perseverance Mars rover and Ingenuity helicopter drone. Images are furnished by NASA [14].

Artemis program as it will create a sustainable existence on the Moon, which is expected to be achieved by 2030 [12].

More recently, the successful landing of the perseverance rover excited the research community as well as the public. The main mission of the perseverance rover is to search for traces of ancient life and gather what could be the first rocky samples from Mars that will be sent back to Earth [13]. The most promising samples will be packed for return to Earth with the later missions. Controlled flight was performed on another planet on Ingenuity Mars Helicopter, which was carried by perseverance. Fig. 5 depicted the images of curiosity and perseverance mars rover and ingenuity helicopter drone.

However, establishing a permanent human presence in space requires a huge foundation to be set. Providing a suitable environment before humans' arrival to the space is necessary. Due to the obvious challenge of distance and habitability of the environment including solar radiation due to tick atmosphere, which requires remote preparation of the environment. This demands various activities that require a multidisciplinary effort. Moreover, with the current technological and economic limitations, it is difficult for humans to prepare the environment themselves Transporting all the necessary resources is very expensive. Therefore, the next focus of exploration should export more know-how and experience to use self-executing, self-managing, and self-sustaining activities. For example, human arrival needs basic facilities, such as air, water, food, shelter, radiation protection, even more, advanced needs but are very necessary for longer presence, such as manufacturing of utilities, ingredients, and even devices, such as mechanical units, computational devices, communication devices, manufacturing units, and spare parts. Therefore, the main target would be to put much effort into exporting well-equipped and advanced robots, drones, rovers, and other IoT devices for the study and preparation of the environment. These are also the trends followed in the research community.

For the space industry to thrive and expand to massive exploration, there are tremendous challenges that required to be undertaken in this era. In this article, we focus on exploring the challenges of enabling communication in the remote environment with a special emphasis on the Moon and Mars. Communication would facilitate the studying, understanding, and preparation of the environment for human presence. Moreover, to realize space exploration missions, communication plays an important role. There is a great advancement in communication technologies. However, to use the existing communication and computational technologies for space exploration, it needs huge progress in adopting and providing connectivity and coverage in facilitating the exploration missions.

This is because the possibility of using IoT technologies, advanced robots, land rovers, remote monitoring, manufacturing for space exploration requires vast, reliable, diverse, and sustainable network coverage [15]. The communication between IoT, such as robots, lander rovers, humans, Moon, and other IoT devices, such as sensors, actuators are required in a mass exploration, which is the next step after several small but reveling missions, such as the arrival of perseverance robot indicated earlier.

Providing mass connectivity for massive exploration mission require transportation of critical equipment for the massive development, deployment, installation, configuration, service provisioning, maintenance, and network management. This requires advanced techniques and methods to create a functioning network in remote areas as far as geostationary, Moon, and Mars.

So far some communication between Mars and Earth goes through revolving satellites, which gives an advantage for continued communication as the two planets revolve around the sun. In any case, the main challenge of communication between remote destinations is the substantial delay due to the distance from the Earth. In this article, we deal with the provisioning of network communication for the Moon and Martian missions considering the impact of the long delay in controlling the robots, rovers, drones, and other IoT devices. The controlling is explored from various perspectives, such as controlling of the devices, controlling of the network providing the network coverage, controlling of computational resource provisioning through data centers.

In general, this article surveys existing works in IoT, computing and data center, control system, communication and networking, intelligent manufacturing (IM), and artificial intelligence (AI) for space application. The survey is unique in that it explorers the necessary computational and networking technologies that could be used for massive space applications. We have outlined the scientific challenges, exploring the research gap that should be addressed where any interested readers and scientific community could work on toward a possible solutions. Here are summary of the challenges and opportunities of massive space exploration that we have identified.

1) Challenges of automated processing and IM for massive space exploration: in space environment, we have limited control and human intervention in addition to physical environment that could incur an expected interruption to any manufacturing or networking or computing process. Remote controlling from Earth station are not always feasible due to the enormous distance between Earth and space station or target device or system in space.

2) It is challenging to adopt and use IoT devices for massive space exploration as it requires either transporting or producing the device to the target sites. Moreover, it requires installing, interconnecting, configuring, monitoring, and controlling of the devices to give a useful functionality in the exploration objectives.
3) Challenges network automation for space: The network should also be managed autonomously. Network automation is an active area in the scientific community. Contextualizing the current ongoing works considering space is also an interesting and necessary area to work on.
4) Challenges of providing computing (edge/cloud) data center in space: We are in the age of network softwarization, control automation, intelligence and cloudification of various type algorithms and functions. This requires computing devices to execute tasks, services, functions, and perfume various type of analysis, such as soil content of a given environment, detail weather conditions of the plants' various geographic locations and time. These all require huge computing resource that should be availed in space especially in case of massive space exploration.
5) Challenges of control system for massive space exploration: Control systems have various applications especially for space applications. The added distance and limited computing, communication, and energy infrastructure along with an exotic environment in space requires innovative research solutions.
6) Challenges building robots for space exploration' and enabling dexterity for massive robots and IoT device collaboration environment: The ability of robots to independently work various type of works is mandatory for space application. Moreover, they should also be able to work collaboratively and cooperatively in a massive tasks as a task force in space environment. Such challenges has to also be investigated.

We have also identified and outlined the scientific, economic, and social opportunities of massive space exploration.

1) Addressing the abovementioned interdisciplinary subjects would enable various opportunities in terms facilitating the space environment for human arrival.
2) Massive space exploration will create various jobs opportunities in various fields. As the space technology grows, human exploration of the space for various application would enable an enormous increase in the global economy, including important and vital but rare-Earth elements and natural resource exploration and utilization in the space industry as well as transportation to Earth for ordinary and essential use
3) Moreover, this will open-up a wider space exploration opportunity from various perspectives especially accelerating national and global space economy.
4) Furthermore, the technology that will be developed could be used for earthly applications.

The principal contributions from this work are summarized as follows.

1) Explore controlling aspects of mass exploration missions.
2) Survey and organize important technologies and concepts on IoT, computing and data center, control system, and communication and networking.
3) Explore the concept of IM for space application.
4) Identify the challenges of providing control, network coverage, and management, producing useful tools and equipment in Mars for mass space exploration missions

Other investigative work is arranged as follows. Section II shows the application of the control system concept for massive space applications. Section III discusses the concept and literature work in teleoperation, telerobotics, and telepresence. A discussion of important computational and communication technology is presented in Section IV. Section V presented a recent advancement in IM. The digital twin (DT) concept is also discussed in Section VI. The challenges and opportunities that necessitate the need for investigation and improvement of existing computational and communication technology are shown in Section VII. Finally, Section VIII concludes this article.

II. CONTROL SYSTEM FOR MASSIVE SPACE EXPLORATION APPLICATION

Martian or Moon missions so far are committed to scientific discovery of the planets and Moons, respectively. The rovers are controlled to navigate through the surface of the remote planet or Moon. For example, a rover navigates through the Martian surface, moving from one area of Mars to another area. However, considering the rocky surface of Mars, moving from one place to another is a key challenge. This is mainly because of the transmission latency among Earth and Mars. On average, it takes approximately 20 min for a message to arrive from Earth to Mars or vise versa. Unlike remote control that can be performed on Earth, such as remote driven cars, the operators of rovers on Mars could not immediately see and control what is happening to a rover at a particular instance. They cannot transmit instant commands to prevent the rover from moving toward a rock or tumbling from a cliff. Therefore, remote controlling of rovers, IoT devices, and other exploration equipment are a challenging task to perform considering the delay. For that reason, a set of tasks or instructions are sent to the rover or remote device at a given time so that the device can execute them autonomously. For example, in trying to operate on Mars; at the start of every cycle, the rover is given a group of instructions. The instructions are sent

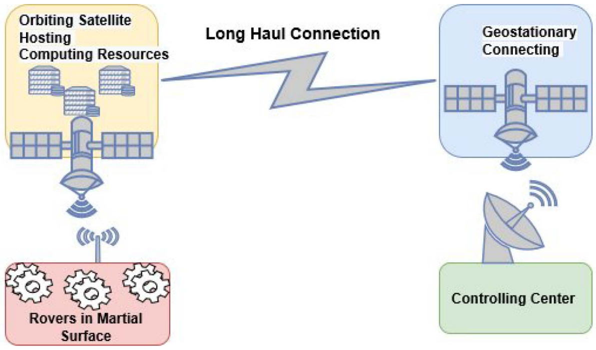

Fig. 6. Example of controls system for space application using edge computing.

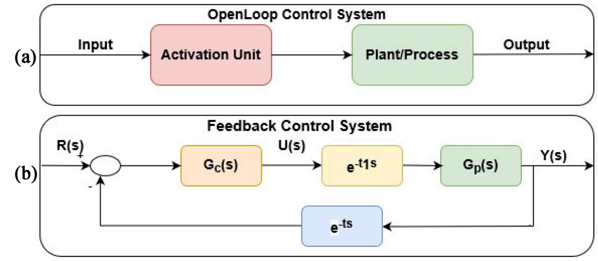

Fig. 7. (a) Open-loop control system. (b) Feedback control system.

by the operators on Earth. The set of instruction sequence provides the rover, which area to navigate through and what kind of experiments to perform in each cycle. The rover can travel over a given distance autonomously using the instruction set. It can locate itself accurately with respect to a destination point, while deploying its instruments to take closer images. It is also able to analyze the content of the rock and soil in terms of minerals or elements.

In the case of massive exploration, multiple robots, rovers, drones, other IoT devices are required to be deployed. For such types of exploration, massive and collaborative deployment of robots will be required creating a heterogeneous environment. This complicates the overall controlling of missions as it is required to have a mechanism to control all devices performing multiple tasks in parallel. Such missions are also sophisticated the required collaboration, coordination, and cooperation between the various type of IoT devices involved in the mission. Since massive and heterogeneous robots and other IoT devices are expected to be deployed, it could be challenging to have a single fit all-controlling technique to apply in a mission of such sophistication. Fig. 6 shows an example of multi-stage with multi technology based system applied for space application.

This section concentrates on the essential control concepts from the basic aspects up to the most recent development. We also look at the concepts and aspects that could help in massive explorations, considering future technologies, such as edge computing.

A. Control System

Control systems play a crucial role in space exploration. A control system is a technique that handles, controls, instructs, or regulates the processing of a system or devices, or environment using a controller. A given control system comprised of connected elements, which are devised to accomplish the desired objectives. These objectives are design strategies for improving various processes, such as manufacturing processes, efficient use of energy, advanced automobile control, and maintaining equilibrium or steady-state behavior of a given system or environment. The objectives of a control system depend on the desired behavior of the plant or process to be controlled. This objective might be to do a $Y(t)$ output, behave in a desired manner through handling entry $X(t)$. The simplest goal could be to maintain $Y(t)$ as low or as close to an equilibrium point as possible. That is considered a regulator problem. In other words to keep $Y(t) - U(t)$ small for $U(t)$, where $U(t)$ is a reference or command signal [16].

Control systems can be classified considering some parameters. For example, considering the kind of signal used, they can be classified as continuous time and discrete-time systems. Moreover, based on the number of inputs and outputs present in the system, control systems can be classified as single input single output control systems and multiple-input multiple-output control systems. They can also be classified as the feedback and open-loop control system based on the feedback path. We first briefly define two families of control systems. We then take a detour to discuss the proportional integral derivative (PID) control systems. We then focus on the literature works based on feedback control systems and proceed to other essential concepts that could have application for massive space exploration, such as feedback control with delay, feedback control over a network, and a control system for a multiagent-based autonomous system.

B. Feedback and Open-Loop Control System

As indicated earlier, we will focus on the two classes of control systems: open-loop control system and closed-loop or feedback control system. In open-loop control systems, the controller control action is distinct from the controlled process parameters. An interesting exemplar of an open-loop control system could be using a timer to activate home ventilation for a given amount of time. In a feedback control system, the control action is dependent on feedback from the process, which is measured using sensors as the value of the measurement of process variable. Fig. 7 shows examples of both types of control systems [16].

C. Basics of PID Controller

PID is a loop mechanism employing feedback controllers. It is applicable for systems that require modulated control continuously. In a PID controller an error value $e(t)$ is calculated continuously, calculating the difference of the required setpoint and an actual observed process variable. Using this, a correction is applied using proportional, integral, and derivatives terms. That is where the name PID originates denoting P for proportional, I for integral, and

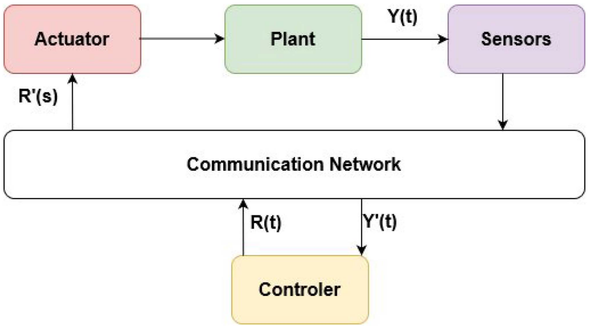

Fig. 8. NCS.

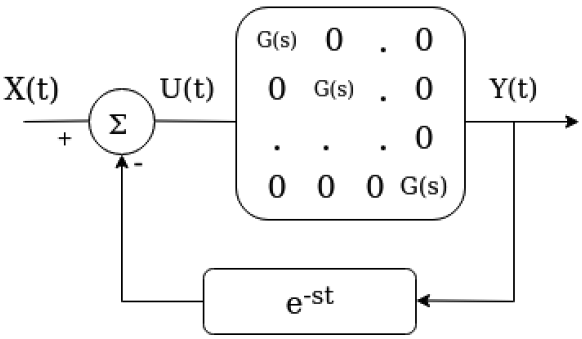

Fig. 9. Multiagent-based control system.

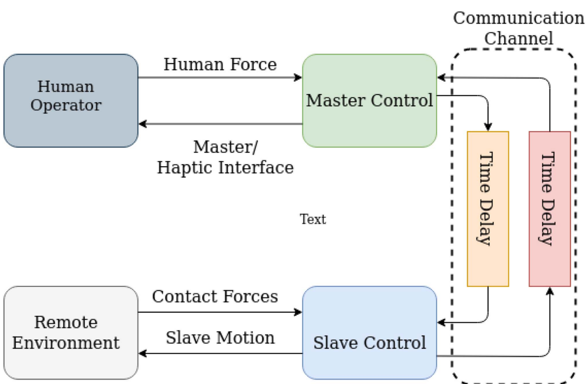

Fig. 10. Teleoperation.

D for derivatives. PID is a widely used controller system. This is because, it is proven to provide reliable operation with an optimal performance while having a straightforward structure. In a PID controller, it is crucial to properly tune the PID controller. Using different mechanisms, PID adjust in an offline fashion. However, due to the parameter variation and disturbances that could be happened in the model, the demand for using the online tuning of PID controller parameters arises. A study of the robustness of optimized adapted offline PID controller and the supervised Fuzzy PID controller is given in [17]. Several techniques are available in the literature. In [17], the authors focus on a fuzzy supervisor. The fuzzy supervisor replaces the human operator role when setting up the online PID controller. Because the fuzzy block require proper adjustments, the authors used an algorithm called the “ant colony algorithm.” The algorithm is relied on the behavior of ants for food gathering.

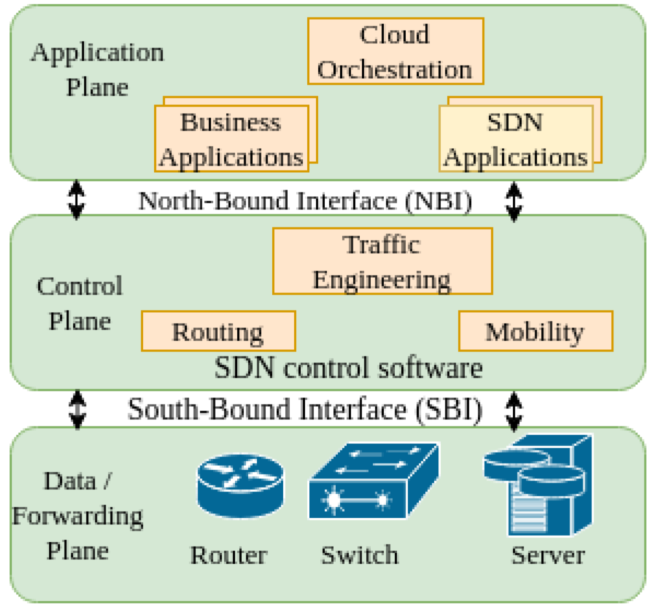

Fig. 11. SDN management architecture [129].

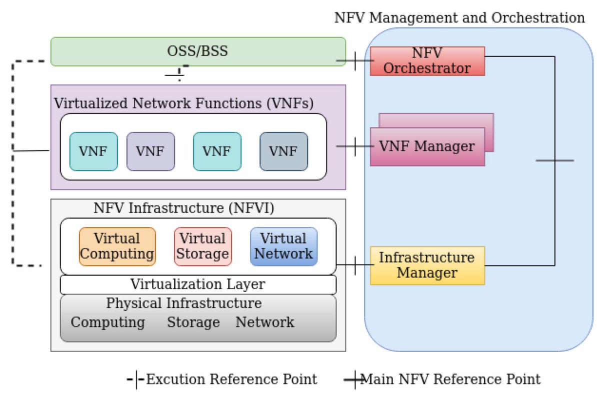

Fig. 12. NFV [130].

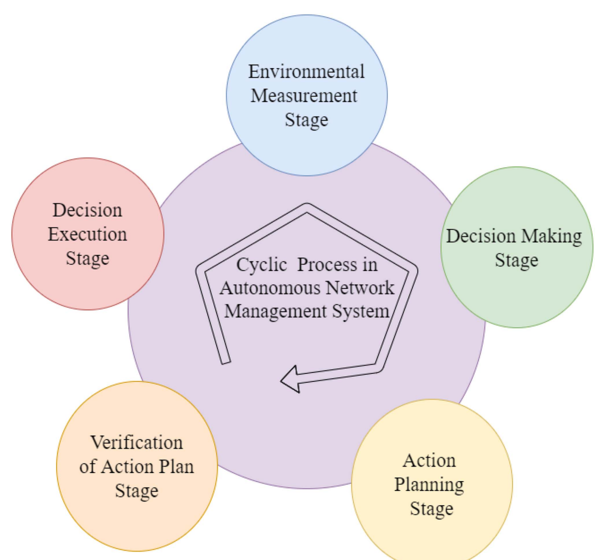

Fig. 13. Network management cycle [129].

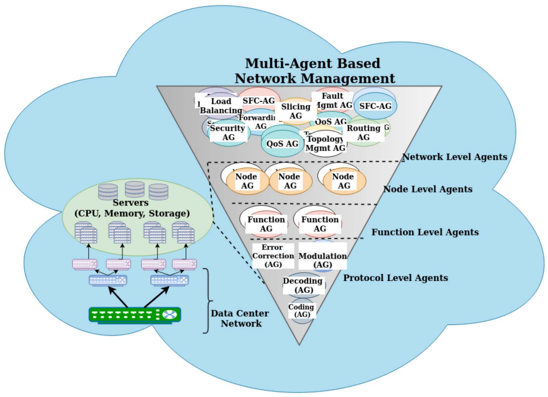

Fig. 14. Autonomic network management system [129].

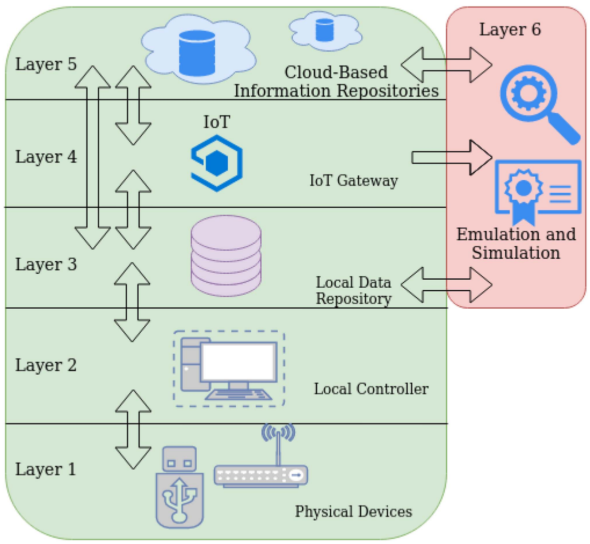

Fig. 15. Six layered architecture for DT: A manufacturing deployment scenario [165].

In [18], a hybrid fuzzy PID controller modeled for a mobile robot is presented. It uses an "MSI Ihomer robot" in the experiment. The robot has a DSP control board and sixteen infrared ray sensors, 24 supersonic wave sensors, and two DC engines. The authors indicated how the conventional PID controller and fuzzy PID controller were not improving substantially. Therefore, they identified the hybrid fuzzy PID controller as a better one with an effect. This is because of the possibility of adjusting the control percentage of PID and fuzzy. Fuzzy controller is simply used for fine-tuning, unlike fuzzy PID controller. The fuzzy PID controller is mainly controlled by the PID controller. They also improved the dynamic response of the robot by effectively reducing the dumping period and overshoot in improving the mobile robots performance. The authors in [19] discussed a fuzzy fractional PID controller by considering its application to a rotating servo system. Another work in [20] discussed a controller for servo control system proposed fractional order PID. An adaptive PID controller to control the maneuvering speed of the BLDC motor is proposed in [21]. The authors in [22] presented a position control of a 2 degree of freedom rotary torsion plant using a two-degree of freedom fractional order PID controller. Recent work in [23] discussed a design of self-adjusting PID controller using computational particle swarm optimization algorithm.

Due to the vast distance between the controlling station and the device to be controlled, there is a tremendous challenge to tackle delay, instability, and disturbance in the communication signals. The application of a control system for teleoperations is a core area that we discuss in the coming section. A space teleoperation application of controller is presented [24], which is based on an active disturbance rejection technique. Similarly, targeting space applications, the research work in [25] presents an assessment of digital pulsewidth modulation model. The model is for converters with zero voltage transition phase-shifted full-bridge.

D. Feedback Control System With Delay

Signaling latency is the principal reason for the instability and mediocre performance that often occurs in pragmatic control systems. The systems control considering latency has been an interesting areas in the control research community [26]–[28]. Latency incurring control systems are typically complex to work on mainly due to the type of functional differential equations involved. They are dimensionally infinite in contradiction with a regular differential equation. There are two generally considered techniques for stability analysis and control synthesis of latency control systems. This include the frequency domain approach and the time domain technique [29], [30].

Several types of research have been conducted to address the problem of stability due to delay [31], [32]. In [31], the authors presented a model predictive control loop this created and applied in a digital controller. Its goal is providing state information through prediction. To produce a lower order digital controller, an efficient model reducing technique is applied. The lower order digital controller is utilized as the adaptive a model reference controller. Following a specific performance, the controller could control closed loop systems having long latency.

The article in [32], considers an optimal disturbance avoidance for discrete-time control systems by latency of control input. The system with latency of control input is converted to a nondissociated system with a disturbance, using a variable transformation. A transformation is done to have a relevant format of the quadratic performance parameter of the optimum monitoring check. Using the Riccati equation along with a Stein formulation, the feed-forward control principles along with state feedback, a disruption feed-forward, and a control memory term is derived. To make the feed-forward compensate and physically realize, a disturbance control system state observer is formulated.

The work in [33] provides a solution for the infinite delay systems in terms of stabilization stability. It focuses on a more general problem. However, it is also more challenging to handle compared to systems with a bounded delay. Based on a general design of infinite delay control systems and a newly approved main methodical lemma, numerous novel Lyapunov theorems are established for uniform asymptotical stability and exponential stability.

E. Feedback Control Over Network

A plant/process could be controlled from a distance using a network by creating a networked control system (NCSs). NCSs are systems distributed spatially where a shared communication network supports the transmission from sensors to controllers and then to the actuators. In comparison with legacy direct control systems, NCSs are easily to preserved and diagnosable, more flexible and less wiring, etc [34]. Moreover, using computer network for control systems has numerous rewards in terms of reconfigurability, low cost of deployment, ease of preserve and operation, and suitability for big geographically distributed systems. These kinds of systems also have a huge application, such as remote exploration, such as Moons, planets, undersea, Earth pole, and other remote areas [34].

However, latency due to the network and other characteristics of communication channels reduces the performance of closed-loop control systems. For example, instantaneous availability of information from sensors is usually assumed in traditional control system modeling. Moreover, information from sensors or actuators is also presume to be complete and uninterrupted. However, in NCSs, the network imposes constraints, such as delay, packet dropouts, and jitter, which could result in the instability and poor system performance of the control system. For instance, NCSs could have a different channel than control inputs with different time frames [33], [35], [36]. This prohibits the steady operation of connected real-time systems [37].

To overcome the effects of latency, packet loss, jitter, and DDoS attacks, various approaches and solutions are proposed [33], [34], [36], [38]–[40]. Some of the approaches followed are model predictive, and stochastic modeling [39], [41]–[43]. The approaches are vary depending on the target application or the problem aimed at solving. An interesting older survey of NCSs is presented in [44]. To provide a deeper understanding of NCSs, the authors reviewed several works on parameter estimation, system analysis, and controller system synthesis. They surveyed research work addressing channel limitations using packet loss, bandwidth, sample rate, and communication latency.

Usually, the network induced latency is random. Moreover, packet dropout and random delay could be approximated as delay. A predictive-based functional control study along with the application for NCS are presented in [42]. They proposed a better "predictive functional control (PFC)" algorithm considering the random short-time delay and longtime delay induced by the communication channel in NCSs. The authors in [41] provided a model predictive-based NCS strategy with stochastic time delay. The mechanism is aimed at overcoming the adversative effects of random latency of an NCS.

Similarly, utilizing the Takagi–Sugeno (T–S) fuzzy model, the authors in [39] presented a networked predictive control algorithm. The algorithm is developed utilizing extended T–S fuzzy models. Using these models, a Toeplitz equation is presented. It is a fuzzy comprehensive predictive control algorithm, which utilize Markov uncertain delay and subspace. The complete optimum control entry is achieved through the fuzzy "mixing" of all subspace control laws, introducing subspace Toeplitz prediction equation.

In principle, packet loss happens intermittently in the controller to actuator and sensor to controller links. Considering random packet dropout in a network control system, the article in [43] analyzes the nonlinear system for H fuzzy anticipating control. They modeled an H fuzzy anticipating controller to make the closed-loop system stochastically stable while preserving a assurance H achievement. In describing the unreliable communication, random parameter that meets the random binary distribution of Bernoulli is used.

Some research work focus on NCS with long delay [45]–[48]. A study of long delay NCS is discussed in [49]. The article considered a class of NCS with long control and output delay. The step is utilized in fixing the control latency. An observer is designed to compensate for the output latency, assuming the NCS model is given. Using the distinct principle, the control system design method is presented, while the design technique of the observer is provided with switched system theory and linear matrix inequality (LMI).

An approach to observing system statues for NCS with long delays is shown in [46]. The authors presented a redacted order state observer method for the system design. By providing the low-order status monitor to recreate the full-order state vector of the initial model, they show that the stability of the state error dynamic characteristics could be assured. The authors developed a low-order status monitor for discrete-time NCS with long delays. The developed target is the—stability in status error behavior. And the low order is the same as the total of unstable (or poorly damped) eigenvalues, which fits a particular system.

A control of NCS having long time delays and using—operator had also been studied in [45]. In [45], the authors considered the random control problem of NCS. For NCS affected by random delays in the networks, an optimal control law that minimize the performance cost benchmark is developed. Utilizing dynamic programming, the state feedback and output feedback control laws for the NCS in the operator domain is devised. For an NCS having long-time delays, the developed optimal LQG controller could be utilized as a delay compensator. A time-delay compensation technique relying on timestamp and fast implied generalized predictive control is provided in [47]. It is a predictive control mechanism for an NCS imposing a long-time delay. The system is constrained to stochastic delays in the network.

An interesting technique, having a random long time delay called incremental PFC for NCS, is proposed in [48]. Based on the NCS's random long-term delay, the proposed system uses the IPFC strategy applied to NCS. The PFC multiphase prediction strategy is used to anticipate the time during the networked transmission, and offset the delay during the transmission. Using buffers, the authors in [50] transformed the original problem into a linear system with constant delay. And they suggested that jitter because of long delay could be resolved using a sequencing technique in the buffers. Similarly, a delay reliant optimum control of NCS is presented in [50].

In [51], a mechanism to design controllers on an Ethernet network is provided. The methodology enables the controller to handle the varying conditions of the workload. Time dependent delays between induced measurements and control for charging conditions. An interpolated and delay-reliant improvement scheduling principle is used to face these variations. Furthermore, by adopting a control method based on events, the lack of synchronization is solved. Then, the calculation of the dual-rate control action is transmitted to a remotely installed controller. On the other hand, monitoring actions and measurements are performed locally at the processing site. Stability is demonstrated through the probabilistic linear inequality matrix.

In [52], the authors proposed a novel network predictive control (NPC) system to address the impacts of delayed communication and lost packages. The author presented stability condition of closed-loop NPC systems. They provided the necessary and adequate circumstances to ensure the stability of a closed-loop NCS with a constant delay. The authors further showed how a closed-loop NPC system, with a limited random network delay, is stable when its matching switched system is stabilized. A modeling and stability analysis of an NCS system is presented in [53]. To model the random long delay NCS, they first use a multi rate sampling approach and an augmented status matrix method. And then, by modeling the systems as discrete-time switched control system, the long stochastic delay impacting the stability of the NCS could be redacted to the problems of the discrete time systems.

By amalgamating the controlled plant with the reference model, in [54], the author discussed the establishment of the closed-loop augmented model. Based upon the control approach and delay formal point method, the exponential uncertainty terms in the sampled system model happened by network-induced long-time delays are converted into sums of formal terms and norm-bounded unpredictability. So, using the Lyapunov–Krasovskii technique, the linear matrix inequality technique and Jensen's discrete inequality, adequate situations for the H-State feedback controllers are achieved that ensure the closed-loop augmented model is permanent and meets the defined H-tracking performance.

Interesting model of the predictive monitoring system for the application of remotely operated submarine vehicles is presented in [55]. This article explains how to implement the predictive controller model in an submarine robot vehicle. While the damping coefficients are disregarded in the prediction of the vehicle location and direction, this article also showed the progress of an submarine vehicle model that consider for hydrodynamic, physical, and restorative impacts. The kinematic and dynamic models of the vehicle are linearized and placed in the spatial state shape within the predictive controller. The model assists to control the next expected position and orientation of the vehicle in monitoring a predetermined submarine line with an optimal level.

Recent work on NCS-based event-triggered output feedback is presented in [56] and [57]. In [56], the work concentrates on controlling the H feedback triggered by an event for network control systems by sampling the time-varying and packet loss. Similar work presented based on event-triggered dynamic output feedback control for T–S fuzzy systems by asynchronous assumption parameters [57]. An optimal control design for perturbed constrained for NCS is discussed in [58]. This article formulated an optimal control design problem for minimizing the communication demand for each system with while ensuring the compliance with state and input constraints.

A time-dependent CDS disturbance suppression using an equivalent-input-disturbance (EID) method is shown in [59]. The control execution of such a model could fall apart by the disruption from the network and surroundings. To address this issue, the authors propose a new approach of to remove an exogenous disruption of these control models. By using the state observer in control model, we predict the state of the plant and an EID estimator to generate the disruption on the control input channel in a real time. For model stability analysis, the system is divided into two subsystems. The stability condition of the control system with a time-dependent latency is introduced using a linear matrix inequality.

The work in [60] analyzed the moving horizon estimation problem for a type of discrete-time-delay systems using the Round Robin algorithm. The transmission among the remote state estimator and the sensor nodes have implemented through a sharing network. In addition, to avoid data collisions, a single sensor node makes it possible to transport data at every instant. In orchestrating the transmission order of sensor nodes, the round robin (RR) protocol is used, in such condition the chooses node gets authenticated to the network can show by using a cyclic function. Furthermore, to reshape the model through a linear system without delays, a lifting technology is introduced. The purpose of the issue is to construct a moving horizon estimator so that the prediction error is eventually limited.

The analysis and design of the NCS taking into account the long delays and the dropping of packets are presented in [61]. The authors used a state predictor in predicting the current states of the plant. Then, the predictive states serve to build the underlying control law. In addition to the state predictor, the NCS by using the data packet dropout and long lag is modeled as a dynamic asynchronous system with event rate constraints. With the help of the model, adequate circumstances of exponential stability for NCS are provided as a matrix inequities. A state-of-the-art approach to controlling the predictive sliding mode for the NCS that takes into the account delay and packet dropout is also discussed in [62]. In this article, Zhou *et al.* [63] provide the adaptive failure tolerance control for an NCS class with an arbitrary time delay by using a neural network. A joint cross-layer optimization in real-time NCS is presented in [64].

One approach is to develop the control systems that do not take into account data dropout and delays but to develop a transmission that minimizes the probability of conditions. Alternatively, the network protocol and traffic are treated as specified circumstance and design control method that take into account the aforementioned questions. Proportional–integral control and network-based modeling for direct-drive-wheel systems in the wireless network is presented in [65]. This article emphasizes the networked modeling and integral proportional control for a continuous time direct-drive wheel system considering wireless network environment. Simplified configuration by the advance system while reducing bus cables and making the height adjustment of the vehicle can simplify. By building an IP control system while consider network-induced delays and dropout of stochastic packages, a new network model is established at the beginning. The control system uses a stochastic impulsive system, which it has two input delays and the system update instants by resetting the equations. For this purpose, two individual artificial delays are used in the characterization of the update of integrated and proportional control signals. Then, a certain mean-square exponential stability and H performance conditions with less conservatism are obtained by using tractable linear inequality matrix. For this purpose, two artificial delays are used to characterize the update of integrated and proportional control signals. Then, a certain mean-square exponential stability and H performance conditions with less conservatism are obtained by using tractable linear inequality matrix.

It is not only network delay or packet dropouts that affect NCSs. Any disturbance in the network could have an impact on the control system, such as network service outages due to cyber attacks, including denial-of-service (DoS) attacks [66]. Therefore, security aspect of the NCS system is also a critical issue. It should be considered as the communication between the plant and the controlling unit are over a network that could be breached or interrupted by network intruders or attackers. An example is a networked control under DoS attacks or distributed denial-of-service (DDoS). An article that considers a tradeoff between resilience and data rate is presented in [67]. In [67], a study of the presence of DDoS attacks imposing a communication constraint on an NCS for linear time-invariant systems is presented. These types of attacks, inhibit communications from being transmitted over the communication network. This article explored the tradeoffs among network bandwidth capacity and system resiliency. The authors indicate the bit-rate circumstance that are relay the unstable eigenvalues of the dynamic matrix of the plant and the parameters of DDoS attacks assuming a class of DDoS attacks. Under this condition exponential stability of the closed-loop system could be assured.

Marian vehicles have used in different applications, such as transportation, military operations, hydrographic, fishing, oil and gas exploration and construction, oceanographic data collection, and scientific characterization. They can also be used in massive space exploration. The tread is to use a multiagent approach to consider the collaboration and coordination of robots in exploring such an environment. An interesting recent article is presented in [68], which discussed an incremental predictive control based on observer of network multiagent systems (MASs) taking into account random delays and packet dropouts. This article addresses the cooperative output tracking control problem for a linear heterogeneous networked MAS with random network-induced delays and packet dropouts in the feedback channel of each agent. The organization of agent consists of a leader agent along with other following agents. In order to compensate for the negative impacts of these random communication constraints, a network-based incremental predictive control system based on state observers is proposed. A network-based T–S fuzzy dynamic positioning controller design for unmanned marine vehicles (UMV) [69]. This article first discussed the network-based T–S fuzzy dynamic positioning system (DPS) establishing a model for UMV. Using the model, stability and stabilization criteria are established, recognizing an asynchronous difference among the normalized membership function of the T–S fuzzy DPS and the controller.

F. Hierarchical Control System

Some control systems, such as industrial processes, often consider the overall control to be carried out hierarchical structure in at two levels. The task of lower layer is the regulatory control and the task of upper level is choosing the set-points of the regulatory controllers. It is worth mentioning that the goal of lower level is that we keep chooses process variables at their desired set-point values and the purpose of higher lever is determining the set-points of the regulatory controllers to achieve the optimal steady-state performance.

In [70], the authors presented the applied theory of control and coordination in hierarchical systems, which are those where decision-making has been divided in a certain way. They focused on different aspects of optimal control in large-scale systems while covering ranges of concepts, such as multilevel methods for optimizing with interactive feedback procedures and methods for sequential, hierarchical control in large dynamic systems.

A mechanism providing multilevel optimization and feedback control for linear time-delay systems has been presented in [71]. Here, the time-delay term is included in the interconnections making the system an equivalent nondelay one. The further analysis employs a standard hierarchical feedback control scheme.

A two-level hierarchical control in a large-scale stochastic system is discussed in [72]. This article presents the summary of the control law for a large-scale stochastic system. The system is comprised of coupled linear static subsystems and the quadratic performance index that should be minimized is taken into account. The problem is addressed in a two-level hierarchical control structure through a coordinator at a higher level and local controllers on a lower level. The authors proposed a suboptimal algorithm, with the possibility of partially decomposing the calculations while carrying out a decentralized control. They have also presented a simplified example.

A method for calculating an optimal control strategy for large-scale discrete nonlinear systems is set out in [73]. It uses a hierarchical fuzzy system. The technique relies on a global system decomposition principle of the interconnected subsystems. The authors then use the differential dynamic programming procedure to obtain the controlling law. For each subsystem, they constructed a limpid-hierarchical Mamdani fuzzy system to compute optimal control laws.

G. Control of Multiple Autonomous Robots

In space application, multiple autonomous robots could be tasked to execute a given mission. However, this requires coordination and collaboration in a distributed environment, resulting in a problem of distributed coordinated control. The issue of distributed coordinated and cooperative control of multiple autonomous agents is currently the most importance research to in control system and robotics. This is mainly because wider applications of MASs in various domains, such as multivehicle localization, multiple robot control, flocking, swarming, alignment of altitude, and communication network management.

The main challenges of remote tasked multiagent autonomous-robots control are the consensus and cooperation of the networked MASs. The work in [74] presents an analysis of the consensus and cooperation problem in networked MASs. They provided a theoretical framework for analysis of consensus algorithms for multiagent NCS emphasizing the importance of flow of information. They also discussed the robustness of varying network system topology considering the case of link or node failures, delays, and performance guarantees. They highlighted the fundamental principles of information consensus in networks and convergence mechanism while discussing performance analysis of the algorithms. The analysis framework is using mathematical techniques from matrix, mathematical graph, and control theory.

In [75], the authors presented a multiagent consensus (MAC) with a time-varying reference state in a directed network considering delay and switching topology. They performed a stability analysis by proposing Lyapunov–Krasovskii functions. Even if the network delay is affected, satisfying conditions using linear matrix inequalities were given to guarantee an MAC on a time-vary reference state under random variation of the network topology. A consensus problem in networks of agents with switching topology and time-delays is discussed in [76].

Moreover, consensus in controlling multiple autonomous underwater vehicles (AUVs) recovery systems in the case of switching topologies and delays is provided in [77]. An AUV and UAV perspective analysis for advanced autonomous mission planning and management systems is presented in [78]. Similarly, an application of a hierarchical control system for AUV first discussed in [79]. They proposed a discrete-event model for the leader AUV operational modes switching as a reaction to environmental changes, previous and current modes, and design a supervisor providing language-based specification on an AUVs formation movement. Moreover, an improved version of the hierarchical control system for AUVs has been presented in [80]. They propose an architecture for a control system with three levels. This article provides a mechanism to the problems connected with the design of each level. At the upper stage, they provided a solution for group recharge scheduling problem. At the middle stage, the solution focus on formalization and control problems of discrete-event-based systems. And at the lower stage their solution targets a cooperative path-following problem.

III. TELEOPERATION, TELEROBOTICS, AND TELEPRESENCE

The remote operation could be on the ground, air, under the sea, or in space. Operating in such an environment is difficult for humans through physical presence. Teleoperation, telepresence, and telerobotics are the main mechanize to solve the problem. Teleoperation is the operation of a system or machine at a distance. Telepresence on the other hand allows a person to feel as if he is present at a remote location than the actual location, to give the appearance of being present, or to have an effect, using telerobotics. Telerobotics is a branch of robotics that deals with the control of semiautonomous robots from a distance mainly using wireless networks, such as Wi-Fi, Bluetooth, the DSN, or tethered connections. In this section, we review the three aspects providing the most important work and progress in the literature.

A. Teleoperation

Teleoperation has various applications, such as remote surgery/telesurgery, military and defensive applications, security applications, underwater vehicles navigation, forestry, and mining applications, and space applications. Here, our main focus is on space applications. To enable humans to travel the vast distance to space and operate a device or a vehicle in space demands a number resources, and suitable conditions in the device vicinity, specifically for the currently targeted Moon and Mars exploration. In the case of sun and other plants, it could be impossible to physically visit with humans or robots with ordinary equipments due to the extreme heat. Hence, it is more appropriate and efficient to use teleoperated devices, such as specially designed rovers and extraterrestrial UAVs. The recent successfully landing of NASA's perseverance is a great example that has also transported a UAV called ingenuity. Perseverance rover carried ingenuity to Mars and successfully released it to make a flight test. The aim of the Mars helicopter is to test the possibility of flying vehicles in the Martian atmosphere.

Teleoperation is a long-sought subject in the research community. Considering environment, operator, and task adaptive controllers systems for teleoperation, the authors in [81] presented an interesting survey. The authors classified the existing approaches that focus on the environment, operator, or task specific (EOT) information within the controller-structure called EOT-adapted controllers. For each method, they have also provided a study of the improvements and requirements. Based on their analysis, they indicated that several mechanisms need either the use of more sensors or require accurate model assumptions.

The most challenging aspect of teleoperation in space application is the delay due to the vast distance between the operator and the target environment. It is because control data must be sent to and returned from the remote environment, which poses a significant delay for real-time control. Therefore, flight control is not observable from the controlling site in real time. The authors in [82] presented a control technique for bilateral teleoperation of a pair of multidegree of freedom nonlinear robotic systems, in the case of persistent delays in the communication network. The presented technique uses a simple proportional derivative control. Master and slave robots are directly connected through spring and damper on the delayed imposed channels. By combining the controller passivity's principle, Parseval's identity, and the Lyapunov–Krasovskii method, they pacify the sum of the communication network and control part robustly delayed altogether. The idea relay on the assumption that delays are finite constants. Moreover, an upper bound for the round-trip delay is known.

Despite the development in teleoperation technology, the old-fashioned method of teleoperation works based on the human operator, which the human operator does the exercise more all the times or does a less direct control. Developments in teleoperation have given rise to complex telepresence models in which the operator can observe its presence on the teleoperation part. It is worth mentioning that most researchers invented better teleoperation methods for complex tasks. Those complex tasks can be done by using the stereo vision and anthropomorphic manipulators using force feedback. Lichiardopol [83] presented an advanced teleoperation systems with their various applications and the control problems that deals with the system control community.

Teleoperation is performed using a communication network. For space application, the DSN plays a central role in connecting the remote environment with the Earth. An early study on the use of the Internet is presented in [84] and [85]. In [84], the authors extend outcome on stable force reflecting teleoperation by having the time-delays and the transmission delays changes with time in unforeseeable trend. They showed that stability is maintained as a result of the systematic use of wave filters. In [85], paper attempted to address the challenges of the time-dependent network time delay in force reflecting bilateral teleoperation. The idea is to address the Internet communication problems in terms of time delay due to bandwidth and physical distance. Moreover, the web-based teleoperation of a humanoid robot is presented in [86]. This article incorporates an entire web and controller teleoperation to allow for various applications which control a robot. A fairly recent study based on the drone is conducted in [87]. The authors presented a technique called DronePick, which is a collection of items and teleoperation of delivery. It is controlled by drone by a portable tactile sight. An interesting book on teleoperation and human–robot interactions is presented in [88].

Due to the advance in computing, AI, and communication technologies, the recent trend in teleoperation is to use such technologies in the operation process [89]. It is based on the idea that, instead of a direct human operation, efficiently transfer to distant locations, without being present. This represents a new challenge in this interconnected digital environment. In this approach, humans may experiment and execute actions in remote locations by an agent carrying immersive interfaces for physical sensation. Nevertheless, compromising skill-based performances, technological contingencies could impact human perception. Recommendations to the making of immersive teleoperation systems are provided taking into the account the findings of human factor studies. It is also followed by a sample assessment method. The authors expand a test-bed to investigate intuitive problems that might influence job achievement while users works with the environment through immersive interfaces. The investigation of its impact on manipulation, navigation, and perception depend on achievement measurements and individual response. The objective is to reduce the impact of factors such as system time delay, a reference frame, viewing field, or frame-rate to obtain the feel-of-telepresence. By dividing the flows of an immersive teleoperation system, they aimed at uncovering how human vision and interaction fidelity affects spatial cognition.

B. Telerobotics

As defined earlier teleoperation mean human control of remote sensors and actuators [90]. While telerobotic means human monitoring of semiautomatic systems at a distance. Moreover, it is assumed that surveillance control are equivalent terms to those that apply to teleoperation, or to a distance like as detection, manipulation, see [91]. Supervisory control considers that the human operator that could be acting remotely or at the vicinity of the equipment in the space environment, supervises a lower level intelligence equipped in the teleoperator itself. The supervision is through sporadic monitoring and reprogramming the embedded intelligence whenever necessary for routine or emergencies operations. Telerobotics focus on the fact that the teleoperator transports enough effectors, sensors, and computer intelligence onboard to do basic duties intuitively. It could be by updated control programs over a telecommunications link. For example, in the case of ingenuity helicopter, the flight is conducted based on a flight plan uploaded from the Earth ground, which may consist of a series of waypoints that were telerobotically planned and scripted by operators at the jet propulsion laboratory.

It is easy to explain why a supervisor-controlled robot is preferable to an autonomous robot or an astronaut able to perform the necessary tasks. At the moment, autonomous robots are neither smart enough nor reliable enough to accomplish the simplest and most routine tasks. Astronauts with a necessary radiation closing have been proven to be able perform tasks. However, the costs are extremely high, as are the risks associated with long-term and nonexecuted tasks.

The first remotely controlled and operated robotic system in space environment is presented in [92]. There are numerous basic technologies designed by the space robot that they use ROTEX. Their features are technologies with multisensory gripper, shared autonomy using a local sensory feedback control concepts, and the simulation telerobotic ground station that is equipped with an advanced delay compensating SD graphics. This article focuses on the method of programming the telesensor programming and the prediction simulation used to control the ground remotely.

Very early work on human supervisory and control of the robotic system is discussed in [93]. An earlier study on the modern in space telerobots is presented in [94]. Including common requirements, design elements, and operational constraints, the authors examined the design issues for space telerobotics. They also identified the peculiar challenges for space telerobotics for terrestrial systems. Furthermore, they presented case studies of a number of various space telerobots while exploring the design of key side systems design and human–robotic interaction. They also outline telerobots and operational designs for future space exploration tasks. A review of space robotics for highly level science with space exploration is presented in [95]. Similar survey of space robotics is presented in [96]. This article outline a NASA survey to determine the current activities in space robotics while predicting future robotic possibilities in a nominal and intensive development strive. The space robotics analysis explored both planetary surface operations and space operations. Planetary surface operations include mobility and most commonly associated with robotics and mobile robots exploration. The space operations focus on assembly, inspection, and maintenance. An older report on the development of automation and robotics in space exploration is presented in [97]. Similar to the remotely operated vehicles, which humans explore the depths of oceans from the top, NASA is considering how a similar approach could help astronauts explore other worlds [91]. On June 17 and July 26, 2013, the Surface Telerobotics exploration concept is tested by NASA. In the test, an astronaut in an orbiting spacecraft remotely operated a robot on another planetary environment. For the future, astronauts orbiting other planetary bodies could use this approach to perform work on the surface using robotic avatars. This could be on Mars, Asteroids, or the Moon.

C. Telepresence

Telepresence is the sensing and display technology that displays remote locations to the users such that they feel they are physically there. It is to make the operator feels as if he is actually present at the remote working site. If a enough information, such as vision, sound, and force are collected from the teleoperator site to the operator, then using the reconstruction techniques it is possible form the operator to feel physically present on the site. A simple-camera-based monitoring could create some level of physical presence. However, typically, a more advanced and sophisticated system is used to recreate telepresence. The usual mechanism to produce telepresence are to enable the cameras to follow the operator’s head movements along with other input sensing equipment, such as stereo vision, sound feedback, force feedback, and tactile sensing. In providing a more accurate telepresence, all human senses should be communicated from the remote teleoperator location to the operator site. Caldwell presented an interesting example of multisense telepresence. The proposed system supports multiple sensing input feedbacks, such as stereo-vision and stereo-hearing, head tracking, force, tactile, temperature, and pain. The vision, hearing, and touch senses are comparatively simpler to transmit. However, smell and taste are very complicated. However, these two senses are not that much necessary for machine teleoperation.

D. Augmented Telerobotic

Augmented presence/augmented reality (AR): It is a combination of real-world sensor information and virtua reality. An interesting example of this is an actual camera image with added computer-generated virtual information. In augmented teleoperation, The operator interface is in charge of generating virtual fixtures to improve the teleoperation accuracy. It is similar to virtual presence or virtual reality. Augmented teleoperation is similar to telepresence, except the environment where the operator feels to be present. A computer generates the sensor information is artificially. In tele-autonomy, the robot’s autonomous behaviors along with human commands make remote operation efficient. A survey of AR is presented in [98].

An early work on telerobotic control using AR is discussed in [99]. The use of technology that stimulates the senses of touch and motion is called haptics in telerobotics. Especially in preforming remote operation or computer-based simulation of the sensations that could be felt by an operator interacting with physical objects. This requires research in the following fields: robotic hardware, hand controller, teleoperators with considering time delay. In [100], focusing on the control research, the aspects of haptics in telerobotics are discussed.

In [101], an application of AR for human–robot communication is presented. A relatively recent study on the design of an augmented telerobotic showcase system and its potential security concerns [102]. The aim of AR is to solve the critical problems of network delay, which may lead to teleoperation instability. Such problem can be mitigated by utilizing the concepts of superimposing virtual objects onto the real video image of the workspace, which enables to reconstruct a simulation plan in the local machine. An interesting recent work to improve the collocated robot teleoperation with AR is discussed in [103]. Despite significant progress in human–robot interaction techniques, there are issues, such as natural and intuitive interaction and communication costs. To mitigate these limitations, the authors proposed RoSTAR (ROS-based Telerobotic Control via AR) [104]. RoSTAR is an open-source human–robot interaction system using robot operating system and AR.

In the article, a comprehensive model to augment a stereo-vision system along with the AR is presented.

IV. COMPUTATIONAL AND COMMUNICATION TECHNOLOGIES FOR MASSIVE SPACE EXPLORATION

A. Internet of Things (IoT)

IoT has various applications in our daily life, such as health monitoring, green energy, environment monitoring, smart home, and smart city [105]–[108]. IoT has provided so many applications using computing and wireless networks advancement. Due to this, IoT has caught the attention of researchers and private industries. The rate of interconnected IoT devices is overwhelmingly increasing and continuously growing with time. As more IoT objects are connected, there is an increase of information in the form of data in the interconnected system [109].

IoT for space application is starting to take shape. Currently, IoT in space is at the conceptual development stage than actual applications. It is because of many obstacles to overcome before organizations can start to deploy and use IoT in space for practical applications. However, a different and alternative approach may need to be explored. Spacial on-site manufacturing and utilization of IoT devices are more viable than transporting them from the Earth over a long distance. Both mechanisms have huge challenges before being realized and are sometimes complementary in that what cannot be manufactured or important to initial materials should be transported. What can be manufactured in remote sites could help the exploration paving the way for human transportation and presence preparing for human arrival. This article reviews the most recent research activities on the application of IoT technology for space applications.

This challenging issue is difficult to resolve with the existing infrastructure. It means that there should be a solution with a new concept and approach that takes data rate, performance, and physical environment into consideration in trying to come up with interplanetary communication. When communication and controlling technology are advanced enough, IoT is expected to have immense potential to facilitate and revolutionize space exploration. The peculiarity of space exploration, which comes due to the vast distance to the target environment to be studied has tremendous challenges. The challenge is to effectively deploy, configure, control, and manage remotely which requires extremely expensive operations.

NASA is putting an incredible effort into the adoption of IoT for space application. It has already setup an IoT lab [110] at Johnson space center and other virtual labs in anther places, such as at Ames research center, Kennedy space center, and jet propulsion laboratory. It was setup in the federal government, which has completed the first phase and documentation, searching for an IoT platform and collecting data on the 20 selected devices.

More recently, in another effort, NASA and Stanford collaborated to launch a tiny IoT satellite into Earth's Orbit“[111]. NASA named the centimeter-scale satellites sprites or ChipSats. The main purpose of the IoT satellites is to perform research activities. More than hundreds of them are already in orbit by the spring 2019. First confirmation signals had been received the back by next day. By enabling communication between the satellites, they would like to demonstrate how the satellites can work together. This is necessary if they eventually operate in a swarm.

The launching of TechEdSat-5 nanosatellite, which is a Technical Education Satellite-5, is a specific example of the application of IoT in space [112]. The TechEdSat-5 nano-satellite is a 3 U CubeSat, which sometimes are called as TES-5. The satellite is developed students from San Jose State University, the University of Idaho, and NASA's Ames research center. It is developed by students of. The main objectives of the TES-5 are to establish a better uncertainty analysis for eventually controlled flight in Earth thermosphere. It performs an in-depth comparison of the TES-3 and TES-4 concerning important uncertainty variable of the thermosphere. It also improves the prediction of location re-entry while providing model for return technology from orbital platforms. Moreover, it provides the experimental investigation of independent TDRV-based missions planetary travel. Furthermore, it provides important data to an on-orbit tracking device, which possibly enhance the prediction of discharged debris from the ISS [113].

Lander to Mars-rover communication may require better connectivity in terms of QoS, latency, reliability, and range. Whereas, for environmental monitoring requirements, it can be satisfied with unlicensed LoRa-based IoT equipment for environmental parameters including temperature, humidity, soil content, wind direction, etc. Moreover, the connectivity between the two technologies could further increase the possibility of more types of device interconnection at various locations of the planet and times of the mission. This gives the mission further possibility of exploring more information about the target planet in a single mission. Moreover, the same mission may have single backbone connectivity from landers to the geostationary satellite station or directly to Earth stations. These with the interoperability of IoT networks, the collected information using various technologies could be forwarded through a single interconnection point. Moreover, this enables the processing of each data collected from each type of IoT device at some aggregation point, such as edge computing. The processing of the collected data reduces the amount of integrated data for efficient transmission and interoperability of IoT technologies could enables this possibility [114].

Edge computing has also seen its way in space demanding a new way of designing and transporting satellites. The challenges and functions of edge in space application demand are presented in [115]. A lot of IoT applications have stringent requirements that are impossible to meet with the traditional cloud computing techniques [116].

Space is not free from adverse competitive animosity, which could result in security concerns between major space players in the race for space exploration. IoT devices implanted in space for measurement and other exploration activity could be attacked or hijacked by the adversary. Unattended access or hijacking of a single IoT device or robot or wireless sensor network may result in unintended consequences, in which the sensors could potentially be placed on territory accessible with competitors or adversaries. Therefore, the security mechanism for IoT devices and connectivity networks is of the essence. In [117], considering IoT in space applications, the authors discuss adaptive feedback-supported communication. The suggested technique is to minimize the amount of data in the transmission from the wireless sensors making the task more difficult or impossible for the adversarial observer to intercept. In this sense, it is to take advantage of hiding the sources of wireless communication. In addition, this technique allows the energy savings if a decrease occurs in the transmitted signals from the source node. This allows for longer operational time from a spacecraft or wireless sensor node. In [118], a security framework is provided, which is intended to provide support to IoT device producers. The author proposed a framework called IoT-HarPSecA (A framework and roadmap for secure design and development of devices and applications in the IoT space) [118]. IoT-HarPSecA has three main functionalities, such as elicitation of security requirements, guidelines for secure development best practice, and a feature that supports peculiar lightWeight cryptographic algorithms for software and hardware implementations.

B. Network Coverage, Network Softwarization, and Network Automation

Network connectivity on remote sites, such as Mars and the Moon and communication with Earth are the main aspects that we will consider in this section. There is a great advancement in the networking industry that is implemented as well as under development to be deployed in the near future. These technologies are providing a tremendous benefit in various sectors of human development. These are from simple voice communication to the video call services, from simple computer interconnection up to the worldwide web from simple on-demand video access to the critical for remote surgery. The advancement has enabled various types of devices to interconnect providing worldwide coverage with various types of technologies wireless and wired. To enable this various mechanisms are developed, such as twisted pair cable, coaxial cable, and fiber access as a physical transmission. The same is true in the wireless domain. Several (de)encoding, channel access protocols, (de)encryption techniques, security tools have been developed to enable communication through both wired and wireless. Numerous architectural models, theoretical concepts, implementation mechanisms, have also been developed and continuously improved. In this ection, we review important advancements in networking that could have the potential to be adopted in space exploration.

1) *Backbone Network Technologies for Space Applications:* The existing communication between Moon/Mars and Earth is through wireless links. For example, the curiosity rover, which had touched down Mars, sends radio waves through its ultrahigh-frequency antenna with 400 Mhz to communicating with station on Earth relaying on NASA's Mars Odyssey and Mars Reconnaissance Orbiters. To serve as both its "voice" and its "ears," curiosity has three antennas. They are installed at the back of rover equipment deck. To increase reliability, a back up communication option, the rover is equipped with multiple antennas. There are networks of antennas deployed in three strategic locations of the Earth. They are called deep space network, which are located in the United States (California), Spain (Madrid), and Australia (Canberra). They support NASA's interplanetary spacecraft missions [119]. Each DSN site has one huge, 70 m diameter antenna. The antennas are designed with the largest and most sensitive capability. They are able to track spacecrafts traveling a distance of billions of km from Earth [119], [120].

There is some advancement in satellite-based networks that could be extended to encompass deep space communication. This technological advancement and convergence of satellite communications would provide a converged network of networks, such as a worldwide web in Mars, Moon, Earth, etc. In [121], the authors suggested a potential architecture of space-terrestrial integrated network that integrates the existing Internet, mobile wireless networks, and the extended space network. The architecture is aimed at providing comprehensive services globally that can be accessed anytime and anywhere.

In this regard, the backbone plays a crucial role in interconnecting geographically distributed and vast distant networks. On Earth, the transitional backbone network extends 100 to 1000 km distances. However, when it comes to space the backbone network ranges in millions of km. Thus, it is significantly affected by the distance in terms of electromagnetic wave propagation and physical deployment possibility. The difficulty of erecting a wired technology for space communication hinders the use of traditional backbone technologies, such as coaxial cable and optical networks. The most viable technology that could be used as a backbone network is wireless communication. This could be through radio links as in the case of DSN, microwave links, and free-space optical networks.

2) *Network Coverage Technologies on Remote Environment:* Network coverage in the remote site could take some inspiration from the existing technology that is implemented on Earth [122]. The most convenient connectivity technology that could have an important contribution to space exploration is wireless technologies. For example, a wireless cellular network could be used to provide a wireless access network on Mars [123], [124]. The authors in [124] discuss the possible use of IEEE 802.11 a and b wireless local area network for wireless networks on the Martian surface. They presented modeling of the physical layer. Moreover, Sacchi and Bonafini [123] discussed the communication aspects of Martian missions. They used the deployment of a Martian wireless network infrastructure considering LTE on Mars. Other existing works in the area of access coverage through cellular, drone, and balloon-based network coverage could be considered to adopt in Mars [125]. The physical layer

modeling of the Martian surface is dependent on the Maritain atmosphere and terrain. Depending on the geography of Mars, it also varies from place to place that should be considered in the design and modeling of the physical layer signaling propagation.

Depending on the mission plane, which could be long term or short-term plane, the technological adaptation in providing the coverage could also be considered. Dynamic changes as the exploration mission being executed the technology needs changes over time, e.g., first the mission could be to evaluate the composition of a given place and weather conditions of the same place and time. In that scenario what kind of device should be used, and what kind of rover should perform the task should be defined. Based on the required exploration task the network could be dynamically provided. Moreover, when the mission changes, which could be to check on the other part of the Martian surface such as Eberswalde, Holden Crater a different network dynamics could be configured that could be based on drones or balloons.

The work in [126] presents early results for the modeling the RF considering Martian environment to determine the characteristics of possible wireless, rovers, and sensor networks. The work used commercial available RF propagation modeling software, which are designed for the traditional cellular telephone system planning, along with the topographic data of Martian environment to determine and construct Mars's propagation path-loss models.

A code division multiple access communication system for Mars based on geostationary relay satellite is presented in [127]. This article defines CDMA-based communication network for various assets including rovers and landers on Martian surface, low Mars orbiters, and CubeSats. They are in the vicinity of Mars, and they use a geostationary relay satellite at 17 000 km above Martian surface. Using 8.40 GHz frequency, the assumed data rates are between 50 Kb/s and 1 Mb/s. Farkaš [117] proposed an adaptive feedback-supported communication technique that can minimize the energy consumption of the communication with a spacecraft or wireless sensor nodes.

There are various IoT connectivity technologies with the potential to revolutionize space exploration. The first IoT connectivity technology to be adopted in space is Wi-Fi. Wi-Fi has enabled a networked space exploration. NASA has provided Wi-Fi access by installing the first access points on the ISS in 2008 [128]. Lora could also be the next to provide connectivity in Mars or Moon exploration.

3) *Virtualization and Softwarization:* Virtualization and Softwarization of the network will help tremendously for the following two main reasons: reduction of the need for physical equipment and generalization of the hardware required (general purpose CPU, memory, and storage). Software-defined networking (SDN) is a centralized and programming of networks through a centralized controller. This provides flexibility and dynamic controlling of networks. In remote exploration like that of Mars, SDN is an ideal approach for network operation and management. It provides the possibility of developing a dynamically adaptive network. Moreover, it paves the way for the autonomic controlling of a network through AI. Network function virtualization (NFV) is also an important network technology that provides a software version of network functions that provide the controlling, management, and operation of the network.

A software defined radio (SDR) is a softwarized radio communication system that process various signals, such as coding, decoding, modulation, and demodulation. It uses software for the modulation and demodulation of radio signals in a communication system. Since it is a softwarized technique, SDN will have a huge part to play in the future communication network for space exploration missions that can potential benefit a lot from SDRs. It can be developed to have an adaptive algorithms, such as machine learning and AI. Currently, there are huge development in the military and terrestrial application of SDR [131]. However, a lot has to be investigated in this area for space mission.

4) *Network Automation:* Automated network management is necessary for deep space exploration due to the difficulty of human presence in space. Network automation is the ability of a network to autonomously manage itself. Autonomic networking is scales up the management capability in addressing the expected dynamic growth networks. Due to the obvious reasons for the unavailability of humans to install and manage the network, we require the following capability of a network that should be deployed on Mars.

1) Self-Installation: Installing hardware equipment is required to provide coverage. Once the required equipment is delivered in the appropriate places, the network equipment has to install itself. The delivery could be through a Martian rover or drone. The installation could require digging holes on the marian surface to fix the antenna or other required hardware equipment. The digging, placement, and fixing of the hardware may need to consider the marian surface for dust and rocky areas.
2) Self-configuration is a feature of a network to configure itself using predefined policies to achieve a particular control and management performance. That is performed autonomously.
3) Self-optimizing is the ability of the network to utilizes the available computational and communication resources to achieve the best performance dynamically adjusting itself to meet the dynamic demands. The network mostly follows a set of predefined policies and measure its performance to make sure that it satisfies the expectations.
4) Self-protecting ensures that the network can protect itself against any potential security breaches or attacks, such as DoS or DDoS attacks.
5) Self-healing is a capability of the network to discover and resolve the failures automatically in the shortest amount of time possible. This is necessary to protect or re-establish the service in the network whenever failure of any network element happens.

6) Self-drone-based areal coverage of network considering the demands that could be performed using self by a combination of driving drone, autonomous network control and management and drone coordinating controller in unknown environments, e.g., using swarm of drones for network coverage.

C. AI for Space Applications

AI would play a significant role in the massive Martian exploration in a range of areas. This includes the automatic controlling of the navigation of rovers in the Martian surface; areal maneuvering of Martian helicopters for various missions; Controlling of networking management system; performing analysis of the collected scientific experimental data; automated manufacturing of equipment, tools, chemical products (e.g., CO_2), etc. Few works explore the application of AI for space exploration. For example, the authors in [132] presented a technique based on reinforcement learning with a multiobjective approach for cognitive space communications. They presented a hybrid radio resource allocation, control, and management algorithm that leverages deep reinforcement learning neural networks with multiobjective. Communication management between system resources can be improved by observing the dependant variables resulting in conflicting goals, which leads to a better performance. Another interesting work is the data mining application of AI [133]. The authors presented an ML-based telemetry data mining of space missions. An application of AI in aerospace is presented in [134].

D. Cloud, Edge, and Fog Computing

Computing is required to perform various analyzes on Mars or any remote mission. This could be the weather condition soil content, chemical composition of rocks, analysis, and before sending them back. Even autonomic control of rovers, drones, and networks that provides coverage requires huge storage and computational power.

As demonstrated by the recent perseverance rover landing on Mars, it is possible to reprogram the onboard device for a different mission. For the perseverance, after the rover landed, the controller is reprogrammed by NASA engineers using commands sent from Earth to potentially perform mobility based on visual processing. This demonstrates the possibility of complex task execution by a single rover or more collaborative rovers in the future.

However, for massive and complex missions, it may need various rovers, drones, autonomous equipment, or other IoT devices. The collaboration of such a mission requires both network coverage and standard computing. It is possible to fully equip the collaborating devices with internally embedded computing. However, it will be inefficient in a distributed and collaborating mission. Therefore, a cloud-based computing provisioning to a remote mission will demonstrate significant efficiency in availing storage and computing power to the exploration missions.

Computing, networking, and control cannot be alienated in a space mission. Moreover, computing, control, and networking are complementary technologies that could facilitate the Martian massive exploration. Principles of control help for network control, edge computing for networking, networking for clustering, and interconnecting of separate computing units. Computing provides a resource for sophisticated controlling algorithm computation. There are some works on the use of edge for control and management algorithm deployment demonstration. An interesting work on mission-critical service control using edge computing and 5G network is presented in [135].

1) *Teleoperation Using Edge Computing:* Remote controlling of a networked system has been studied as discussed earlier. However, recent advancements in networking through network softwarization and automation, cloud computing, edge computing, machine learning, IoT, UAV, and automation have instigated the need for a new approach considering the current advancement in these cross multidisciplinary domains [136]. Moreover, the target of this literature server is space exploration Martian and Moon exploration in particular. Edge computing is a new computing technology aiding the responsiveness, scalability, and reliability of terrestrial computing and IoT-based sensing networks in space exploration. Edge computing can mitigate the long distance problem between the processing servers and the end users by bringing the resources closer to the end users specifically in space applications. An interesting work on orbital edge computing is proposed in [137], presenting conceptual definition and characterization. They described power and software optimizations for the orbital edge. They also discussed the use of formation flying to parallelize computation in the case of space application.

Since the concept of edge computing in space is relatively new, there are few works on the deployment for deep space exploration. However, an application based on space edge computing is also discussed in [138]. The authors presented a real-time-based motion control techniques utilizing measured latency value on edge computing. Similarly, the work on optimized control design for connected cruise control using edge computing, caching, and control [139] is used for remote operation on Earth, such as Arctic, and marine environment exploration.

This article describes an optimal control design for the system that use edge controllers with respect to communication latency with computing, caching, and control capabilities. It models the motion dynamics of every vehicle in the platoon. Then, it formulates a linear quadratic optimization problem with regard to the network delay and the sampling period. In minimizing the deviations of the vehicle's motion direction and speed, the control strategy is to use backward recursion in solving iteratively.

A recent interesting work using satellite for edge computing for IoT in aerospace is presented by Wang *et al.* [140]. They propose converting the legacy satellite into a space-based edge computing site. This enables to automatically upload and download software in orbit, to flexibly and efficiently share on-board computing resources while providing services coordinating with the legacy cloud computing [116]. They also provided the hardware structure along with the software architecture of the satellite. The work in [141] discussed the application of edge intelligent computing in satellite IoT. Similar work with a focus on latency and energy consumption optimization for mobile edge computing on improved SAT-IoT networks is presented in [142]. The authors in [143] presented a survey on the application of edge computing considering IoT. An interesting recent work for industrial remote control application is presented in [144]. This article explored the use of edge computing for multitier industrial control system.

V. IM FOR MASSIVE SPACE EXPLORATION

IM is the process of automating the manufacturing process with autonomous networking, intelligence, security, and innovations from major technologies. IM is useful for space application. This is because transporting fully fabricated technologies is very expensive. Therefore, the first aim should be to create a self-sustaining environment on Mars. So the strategy should be to transport mostly knowledge, experience, soft techniques, and automation algorithms to establish self-sustaining environments. That is expected to be applied for massive Mars (Lunar or deep space) exploration programs, such as NASA's Artemis program. From a communication technology perspective, what could be transported are automation techniques, such as automated manufacturing of communication units, network assembling, installing, configuring, and management technique, e.g., manufacturing of sensors, antennas, computational units along with self-assembling, self-installing, self-configuring, and self-managing algorithms.

Network support will provide remote operation and control of machines, rovers, drones, and satellites. This enables intelligent industrial operations that facilitate fine-grained control and decision-making, and visibility into the use of exploration and excavation of raw materials, transporting them to storage areas, using them for production, and using them for other functions, such as expanding the network itself, building other robots, and useful tool for human use and even transporting back to Earth. The manufacturing devices will use various communication technologies, such as LoRaWAN, NBIoT, 5G/6G networks that could leverage recent networking advances, such as SDN, edge computing, and network slicing. Manufacturing applications, particularly the ones needing real-time remote control and decision making will need low communication latency and high data delivery reliability difficult to achieve with existing networking solutions for Mars exploration applications. Especially, given the vast distance between Earth and Mars that impose a significant delay making control and manufacturing process impossible to perform. In IM, the network needs to meet diverse demands, such as ultrareliability (decision making), low latency (real-time control), low energy consumption, and resiliency that could be met by a dynamic, flexible, trusted secure, and adaptive network.

The data model could be exchanged among spatially distributed manufacturing agents, rovers, design, and manufacturing Martian sites, through the life cycle stages of the product. That is starts with requirement specification and conception design. And then the detailed design is developed. Then, fabrication and assembly will carried out. Finally, installation, and operation of equipment is done. Early and interesting work on intelligent manufacture is presented in [145]. The authors presented a model of IM systems (IMS) that are based on the multiagent. According to the characteristic of the enterprise information system, the networks setup and the systems construction process utilizes specific methods to meet the requirements. This research work employs the multiagent approach for intelligent manufacture. The multiagent intelligence manufacture system comprises many intelligent agents to support manufacture functions, such as the design, the production, and the demand integrates. This enables the agile manufacture MAS.

The concept of IM is a relatively new concept that is gaining massive attention in research and industry. Its use for space application is in an early stage. In general, it is expected revolution and industrial transformation are driven by information. It uses various advanced information and communication technologies. An application of a digital based flexible IMS for machine and device production industry is explored in [146]. This article reconstructed the physical structure of the overall system. It also provides an in depth design of control system and workshop management, intelligent system for the logistics, and the three flexible digital processing unit. Interesting recent research work on the application of IMS for precision assembly enterprise is presented in [147]. Another recent work in [148] discusses the application of an IMS of sustainable development. The work in [149] also explored IM from the perspective of Industry 4.0 is reviewed. A multiscale challenge of control in IM is explored in [150]. In [151], the authors contribute to the concept and development of a smart factory as a novel approach to an IMS. Very recent work also made an interesting analysis of IMS constructed by the army and the people in the era of the Internet [152].

VI. DT FOR SPACE EXPLORATION APPLICATION

The concept of DT had been proposed recently, which attracted high attention of academics practitioners in related fields [153], [154]. In principle, a DT is a virtualized illustration of a physical object and/or process. It comprises the physical product and the digital version of the product, and information flow between the two products. DT services are becoming popular in the industry in recent years as they take advantage of both physical and virtual world to enhance the life cycle of any process [153]. It has a potential way to realize the interaction and integration between the physical world and information space.

An interesting work on a prediction model of convenience store model using DT is presented in [153]. There are various architectures proposed for the DT. The work in SoS [155] provides strategies for SoS four challenges and four architecture set-ups using DT. In [156], an architecture of a DT to enable digital services for automotive battery systems is proposed. The architecture includes various stakeholders along the production and product life cycle in the case of a battery system. DT facilitates manufacturing and product use for those services. Similarly, an architecture, focusing on a control system and an industrial automation for security application, is presented in [157]. This article focused on how a DT replication model and the associated security architecture could be utilized in allowing data sharing and controlling of security-critical applications. Another architecture for DT pervaded systems is proposed in [158]. Targeting manufacturing a cyber-physical system, the authors in [159] proposed a conceptual design architecture for a DT system.

Various DT technologies are applicable for most recent production technologies. For example, an interesting application of DT for IM assessment in terms of sustainability is presented in [160]. Similarly, the authors in [161] discussed a methodology based on DT modeling and implementation for Industry 4.0. The application of DT for future factory is presented in [162] while considering service oriented architecture. A combination of recent technology along with DT is discussed in [163], for the application in Industry 4.0. The authors discussed the application of adaptive federated learning along with DT for the context of industrial Internet of Things (IIoT). The majority of existing DT use cases, architectures, and technologies described are applied in DT domains. The work in [164] proposes the FIWARE ecosystem, which is a modeling DT data and architecture. It is a building guideline with FIWARE as an enabling technology. It provides the catalog of components along with data models, as a mechanism to solve the development of any DT. It also illustrates how to use FIWARE to build DT using a complete example of a parking DT.

VII. RESEARCH CHALLENGES

Various area of research has to be conducted to bring the existing technology to Mars/Moon in preparation for human landing and permanent settlement. It includes rethinking and redesigning some technologies. That is because of the added challenges of distance and environment, in space such as the Moon, Mars, and other titans. In this section, we will explore some of the important challenges of adapting existing technologies in Martian exploration.

There are several constraints added due to the marian surface and environment. That includes energy, vast distance, radiations, and other constraints due to the atmosphere. These are critical constraints related to the design, development, and deployment of a system for space missions resulting in extremely expensive with prohibitive costs. The most challenging arise due to the long-haul distance between the Martian surface and Earth. This is because of the difficulty of mass transportation of humans and the availability of networking experts in such a vast distance. This results in extreme demand for high efficiency in terms of size, weight, cost, and energy consumption of any device to be installed on the Mars's surface.

A. Automated Processing Challenges

Various activities on Mars, such as navigation of rovers, flying of drones, manufacturing of devices, and management of the network have to be done autonomously. This is due to the vast distance between Earth and Mars that hinder real-time control. Moreover, human presence is prohibitive and expensive in at least the foreseeable future. Therefore, the challenges of automating processes are very necessary. In the existing system experienced on Earth, we follow the following procedure as a general guideline.

1) Planning is to model the physical system, decide on the objectives to meet the requirements, and define a strategy.
2) Teaching is to teach the televise what to do and how to do it.
3) Monitoring includes observing the signals, predicting the current state system, and detecting abnormal behavior of the system.
4) Intervene is how to fix an abnormality including minor or major adjustments, system shutdown. If the programmed action must come to a normal conclusion, it goes back to teaching.
5) By learn from the experience to enhance the next or expected planning.

However, the applicability of such a procedure should be considered for the Martian surface with the added challenges mentioned above. For example, the fourth procedure is to intervene, which is a normal human physical intervention that is practically difficult to perform on Mars. Therefore, it is necessary to have a mechanism to maneuver such challenges. It could be by using teleoperation or autonomous control through reprogramming.

B. Challenges of Automatic and IM for Massive Space Exploration

As we have indicated so far the distance imposes a prohibitive challenge to transport necessary technological devices that are useful to perform the exploration and preparation of the Martian environment. Therefore, autonomic manufacturing, assembling, deployment, configuration, control, and management of experimental devices, IoT devices, rovers, network elements, and other necessary equipment are the key challenges that should be explored for a successful massive Martian exploration. The existing mechanisms could be exploited for maritain adaptation with further improvement to address the added challenges mentioned above. These could be 3-D printing of sensors, actuators, computational units, and IoT devices, in the general building of self-healing electronic materials and using them to manufacture self-healing electronic devices, standard equipment and tools, CPU, and storage. The idea of fabrication of self-healing electronic materials and using such materials to fabricate self-healing electronic devices will be more valuable. However, it is challenging since the technology is still in an early development stage on Earth.

C. Challenges of Adopting IoT Devices for Massive Space Exploration

In the case of Mars, what has been discovering so far about Mars' environment are the things that could be observed by landers, rovers, areosatellites, and telescopes. More observations are required that could be facilitated by the adoption of IoT technologies.

Manufacturing of suitable IoT devices for the Martian surface. The Mars have a temperature cold, dry environment, lack of air, and huge sandstorms. The temperature could go as low as $-90\,^{\circ}$C, as high as $20\,^{\circ}$C, and on average $-63\,^{\circ}$C. There is also the matter of its radiation and atmospheric content and density are some of the peculiar behavior of Mars that differentiate it from Earth atmosphere. Any device operating in this environment should be able to resist and adapt to these harsh conditions. Some mechanisms exist which mainly use protective shields and heating techniques to counter the atmospheric challenges. It is an interesting challenge to provide other techniques to enable devices to service such conditions. For example, it would be interesting to produce devices that withstand such an environment.

There are also other areas of challenges for IoT devices. These include enabling the IoT device to interconnect to each other or connect with an access gateway to collect and process the information at a computational equipped environment such as rover, Martian station, and areosatellites. Moreover, further challenges are also their in-terms of transportation of the IoT devices from the manufacturing site that could be Earth or Martian site. Manufacturing and deployment of IoT devices also pose significant challenges in terms of automated manufacturing of IoT devices in the case of Mars production of the devices. Sensors may not be fixed in a single location but also it could be changing places from time to time for efficiency. Even for installation, they could jump from one place to and another furthers place to deploy themselves but still maintaining the communication between the master or the central lander.

D. Challenges Network Automation for Space

Due to the aforementioned challenges of inaccessibility for humans and sometimes by rovers, and harsh environment, etc., the network has to be managed autonomously. This is also because of the accessibility challenges in terms of the difficulty of accessing the remote network and IoT devices, which mandates the need for self-management of a network. This poses significant challenges in terms of network assembly, network deployment, network configuration, network control, and network management of network elements. Each aspect requires various works that could be novel and/or adaptive techniques should be investigated and developed to enable a fully autonomic network for the Martian surface.

E. Challenges of Providing Computing Data Center Space

For massive exploration, there are large amount of expected data to be produced by the IoT devices. This mandates the need for processing and transmitting only the required and valuable summarized information. It could be inevitable to have edge computing on areo-stationary or ground-based data center. This is because of the prohibitive delay between the remote site and the Earth.

Assembling and creating computational (cloud/edge) data centers is necessary for many reasons. A lot of computational analysis could be performed that included controlling networking devices, rovers, manufacturing units. Moreover, the computation could also be performed collecting the information about the Martian surface that includes, the atmospheric condition, weather condition, soil content, atmospheric content, etc. The network by itself could be based on virtualized and software for flexibility, automation, and other advantages that come with the softwarization of the network. However, this requires huge computational resources. Providing one is a huge challenge that should be addressed. An example could be a modular and agent-based approach on a barred metal that has numerous advantages that include scaling as new functionalities are required. It may require the maturation of generalization of the computation hardware required, such as general-purpose CPU, memory, and storage. This is for the obvious reason that enables the reuse of computational resources as the functionality could be changed. At first, it could be with a small standard CPU and standard computational resources and progressively add and expand the capability. This will also reduce the need for physical equipment.

Assembling and creating computational (cloud/edge) data centers is also a challenge that should be addressed. Interesting current approaches are to convert the geo satellites into computation environment that include hosting computing resource at the ISS. However, it is not the assembling that poses a challenge but also energy consumption of the data center as energy is provided by a solar panel that could less power to run a big data center with huge computational devices. Moreover, it could also possible to have a dedicated ground site as an edge data center that could be used by devices and robots to communicate and get their computation done at the data center.

F. Challenges of Control System for Massive Space Exploration

Mars-Sojourner rover touched down in 1997 and proved that it was possible to drive a vehicle remotely on Mars. Since the first arrival of the rover, which was a technology demonstration experiment on the Mars Pathfinder mission, we have been able to control, operate, and drive rovers remotely. Remote controlling is a crucial part of any remote exploration mission.

The delay between the network control and management center and the actual network prohibits real-time processing and control. That should be addressed by various means that included automated controlling of devices. The challenge also grows as a number of IoT based devices are installed for the missions. Managing and monitoring a number of IoT-based devices also pose a tremendous challenge in a Martian environment with Martian constraints.

Remote controlling of a networked system has been studied as discussed earlier. However, recent advancements in networking through network softwarization and automation, cloud computing, edge computing, machine learning, IoT, UAV, and automation have instigated the need for a new approach considering the current advancement in these cross multidisciplinary domains. Moreover, the target of this literature server is space exploration Martian and Moon exploration in particular. In other words, the target of this article is to embark on the journey to mass network deployment on the Moon and Mars. In particular, this article explores multistage controlling mechanize in which a set of instructions or controlling tasks are sent in batches to the edge where the real-time control over the network would happen for a multiagent-based cooperative autonomous devices operation.

G. Challenges Building Robots for Space Exploration′ Dexterity

Various area of robotic design has to be investigated. These include robot design for a particular mission and performing a specific task that withstands the terrain and environmental conditions of Mars. Moreover, the robots could be designed so that they can perform multiple types of tasks. This also poses an interesting challenge in robots' dexterity and autonomous control. Teleoperator phenomenon is becoming more important these days in robotics. For example, configuring more fingers to grasp, hold, and ungrasp objects gives more degrees of freedom and has more of an impact on the robot's performance. Therefore, multifingered hands have been developed. Although this design would add considerable function, the hardware design challenges cannot be overlooked. Moreover, transporting all the required robots from the Earth is very challenging and prohibitive in terms of cost and technical challenges. Therefore, it would be interesting to be able to have a mechanism for robots to manufacture other robots. The same is true for drones design for various applications, such as wider area coverage and rocky and muddy area avoidance.

1) *Cooperative Robotic for Space Application:* The challenge is not only designing flexible robots with high dexterity and transporting them but also cooperating and coordinating them to perform a given mission. As more and more robots arrive and are manufactured there, the complex mission could be performed. For such a complex mission, cooperation, collaboration, and coordination are very critical challenges that should be addressed. A multiagent-based robotic cooperation on the existing literature could be utilized considering the added challenges of Martian constraints.

VIII. CONCLUSION

In this article, we have reviewed important concepts for massive space applications. We have also reviewed various literature from multiple interdisciplinary areas considering the challenges of space exploration and future landing on Mars and the Moon. Finally, we have presented the challenges of massive space exploration in the context of the areas that are essential to the exploration.

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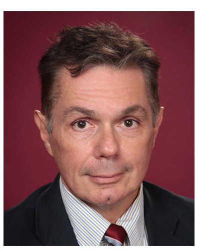

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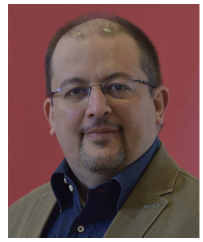

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