Autonomous Robotic Capabilities in Space Exploration: From Mars to Beyond

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Abstract – The historical timeline of automated systems functioning in space settings spans around 75 years, whereas the existence of practical automated equipment to facilitate astronomical observation dates back over 200 years. Over time, physical servomechanisms have seen advancements in both hardware and software capabilities, enabling their successful operation on the Martian surface and even during journeys to the heliopause, which marks the outer boundary of interstellar space. Contemporary spaceflight operations exemplify a growing capacity to provide decentralized coordination across several automated systems, intricate communication networks, and diverse communities of scientists and engineers. This article examines the impact of autonomous robotic functionalities on space explorations, specifically emphasizing the investigation of Mars' surface. The article examines the use of robotic systems in past missions, specifically focusing on their application in activities like as the identification and analysis of water ice deposits, study of geological features, and the deployment of sensor devices. The article further emphasizes the achievements of autonomous operations in missions conducted in Earth's orbit, as well as the progress made in developing autonomy for operations in close vicinity to minor celestial bodies. This research explores the Chang'e 4 lunar mission and the OSIRIS-REx mission as instances of autonomous exploration and sample gathering on minor celestial bodies. The research also encompasses the exploration of prospective autonomy in forthcoming expeditions to oceanic realms and distant locales.

Keywords – Space Robots, Robotic Systems, Autonomous Robotic Capabilities, Attitude Determination, Space Missions, Control System.

I. INTRODUCTION

Space robots are a category of specialized robotic systems designed to supplant human presence in various tasks such as scientific experimentation, extravehicular operations, space exploration, and other related activities inside the realm of outer space. The use of space robots is progressively transforming conventional methods of space transportation, on-orbit building, on-orbit maintenance, and planetary exploration. This technology has significant importance as a facilitating mechanism for future space missions, both unmanned and human. The design, manufacture, and management of space robots pose significant problems due to the unique environment in which these devices would function, differing significantly from that of Earth. The area of space robotics necessitates interdisciplinary collaboration among engineers, physicists, computer scientists, biologists, chemists, and other experts in order to collectively strive towards a shared goal.

The operational capabilities of space robots are significantly constrained by a variety of distinctive obstacles, including communication delay, restricted power sources, and stringent safety prerequisites. The current operational robots in space are either remotely controlled from ground stations or tele-operated. Consequently, much research is now being conducted to enhance the autonomy of space robots. One of the pressing concerns requiring prompt response is the increasing accumulation of space debris, particularly during the last decade, which presents a substantial hazard to operational spacecraft such as satellites and the International Space Station. According to Hakima and Emami [1], the Low Earth Orbit (LEO) now contains about 500,000 debris items. It has been suggested that achieving stability in the space environment would need the removal of around 5-10 objects from LEO annually. Various methods for space debris removal have been proposed, including harpoons, nets, and tentacles. However, the utilization of robotic arms for capture continues to be the favored option due to its potential for extension into other application domains such as on-orbit servicing and assembly, as well as autonomous rendezvous and docking.

Spacecraft need maintaining a standard orientation in order to facilitate the charging of batteries, establish communication with ground stations, and ascertain their own attitude and location. The micro-gravitational conditions of the orbital environment provide a significant problem due to the floating spacecraft bus that the robot-arm is connected to. Any movement of the robot-arm would result in a disruption in the spacecraft attitude. In the case of spacecraft that can free-fly, the attitude determination and control system (ADCS) [2] serves the purpose of continually mitigating disturbances caused by the manipulator's operation. This is done in order to sustain the desired nominal spacecraft attitude. However, it is fundamental to note that this process necessitates a significant amount of energy consumption. The design of attitude systems is a process that involves several iterations. Boles, Piel, and Perreault [3] provide a comprehensive enumeration of the customary stages involved in a design process, together with a delineation of the anticipated inputs and outputs for each respective stage. The procedures involved in attitude systems are shown in **Fig. 1**. The process of determining attitude with certainty typically takes place during ground processing of telemetry data. In contrast, the design of onboard, real-time attitude determination systems prioritizes high reliability and predictable operation. The Attitude Determination and Control System (ADCS) will also rely on other subsystems, including the power and structural subsystems. The requirements of attitude will also need specific criteria for other subsystems, including propulsion, thermal control, and structural stability. **Fig. 2** illustrates the intricate interconnections required to align the ADCS architecture with the overall mission requirements.

The promise for autonomous robotic capabilities to transform space exploration lies in their ability to provide efficient and independent operations on celestial planets. The comprehension of the influence of autonomy on space missions, especially in the realm of surface exploration, has significant importance in the advancement of our understanding of the cosmos and the facilitation of forthcoming human expeditions. This study presents a comprehensive examination of the present status of autonomous robotic capabilities in space missions and emphasizes instances of their effective deployment.

The subsequent sections of the article have been structured in the following manner: Section II presents a discussion of autonomous robotic capabilities in space missions. This section presents its past and present capabilities. Section III focusses on the advances made in landed missions, from mars to the moon, and even beyond. The landed missions discussed in this section include (a) landed missions, and (b) surface missions. Section IV projects the future scope for autonomy and autonomous small body explorers. Lastly, Section V presents conclusions to the research.

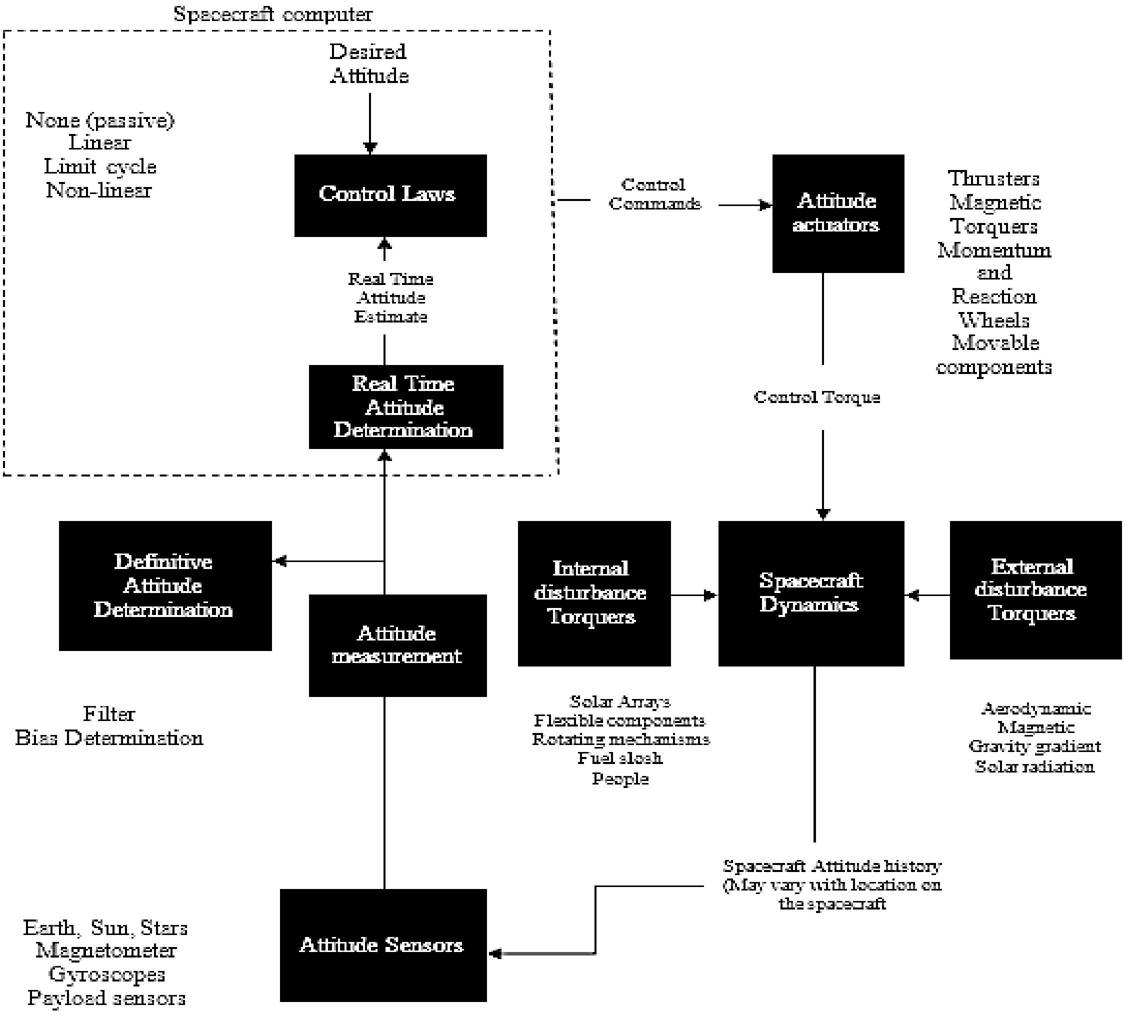

Fig 1. A Schematic Representation of a Comprehensive ADCS.

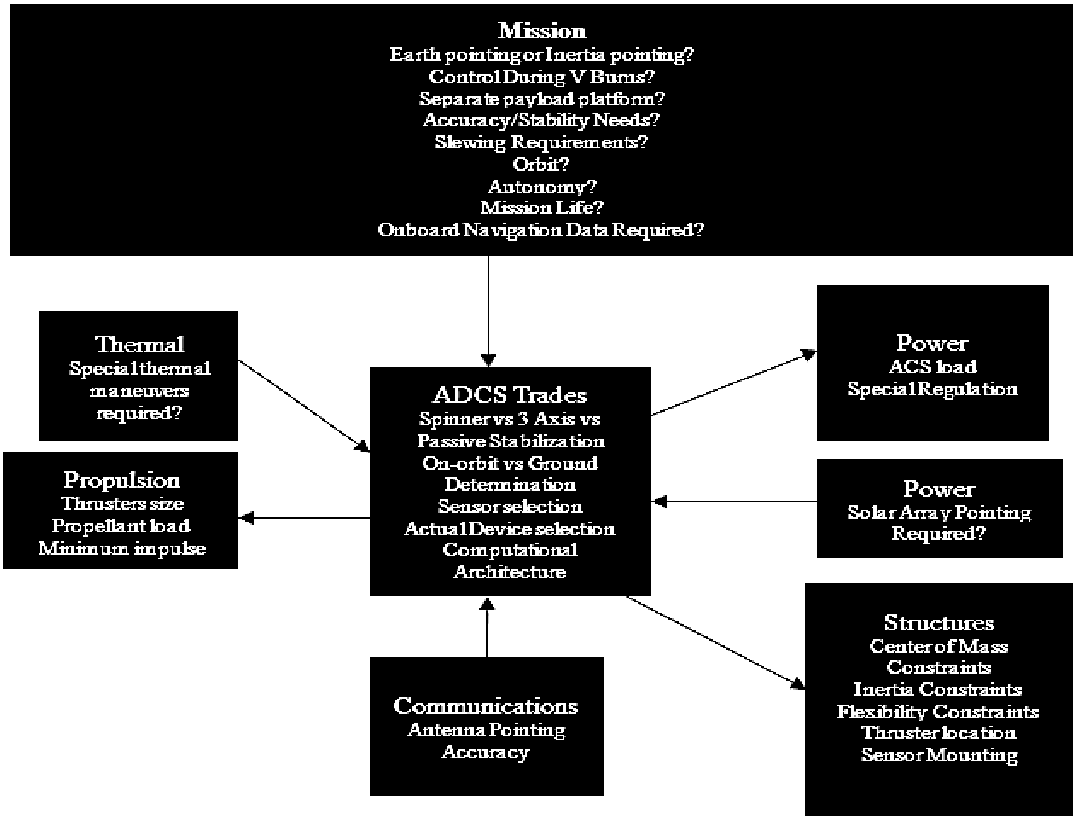

Fig 2. The Additional Subsystems on The ADCS and The Influence of Mission Requirements. The Direction of Arrows Indicates the Flow of Needs from One Subsystem to Another.

II. AUTONOMOUS ROBOTIC CAPABILITIES IN SPACE MISSIONS: OVERVIEW OF THE PAST AND PRESENT

To get insight into the future trajectory, it is necessary to thoroughly examine past experiences. This section presents a comprehensive review of significant previous missions that have made substantial contributions to the advancement of autonomy in the context of space applications.

In the last two decades, there has been a notable observation of the influence of robots in the context of surface exploration on the planet Mars. This integrates the initial 100 meters of Sojourner's trajectory on the Martian terrain, the exploration carried out by Spirit and Opportunity in various locations across both Curiosity`s and hemispheres climb of Mount Sharp [4]. In conjunction with the discoveries made by the Spirit and Opportunity missions, which yielded evidence of historical aqueous activity on Mars, the Phoenix mission employed its automated arm to gather samples of water ice deposit situated in the northern polar region superficial subsurface [5]. The Curiosity rover has undertaken a more extensive analysis of Martian geology in contrast to preceding missions, leveraging its manipulator and mobility capabilities to execute drilling operations to its suite of scientific equipment. Molecules of complex organic have been identified in the regolith of Mars, with the atmosphere showing seasonal oscillations in the presence of low methane concentrations. The InSight project recently utilized its robotic arms to effectively deliver two European sensors on the surface of Mars. These instruments include a very accurate seismometer, which successfully identified a heat-flow and the first Marsquake measuring mole designed to probe several meters into the surface.

In-Space Robotic Operations, Planning and Scheduling

The RemoteAgent Experiment conducted during the Deep Space I mission in 1999 showcased the ability to do goal-oriented tasks by using onboard arranging and execution, as well as model-based fault detection. This experiment included the operation of two distinct experiments for a duration of 2 days initially, followed by a subsequent operation for 5 days [6]. The spacecraft exhibited its capacity to effectively address overarching objectives by autonomously formulating and implementing plans inside the spacecraft, while being closely monitored by model-based fault detection. During the 36 month-long mission, the autonomous navigation capabilities of the spacecraft were shown during a three-month cruise phase. Furthermore, a 30-minute autonomous flyby was conducted, showcasing the spacecraft's ability to detect asteroids, update its orbit, and perform low-thrust trajectory-correction procedures.

During the following decade, the Stardust mission successfully executed a comparable flyby achievement involving one asteroid and two comets. During the period from 2005 to 2010, the Deep Impact mission successfully executed a self-guided two-hour terminal navigation maneuver of a comet impactor, as well as conducting a separate flyby mission that included tracking two comets [7]. The experiment showcased the ability to identify the desired celestial object, make necessary adjustments to the corresponding orbital paths, and effectively control the spacecraft via the use of low-thrust maneuvers. The utilization of autonomy has been observed in the facilitation of scientific operations for missions conducted in Earth's orbit, as exemplified by the Earth-Observing-1 spacecraft [8]. This particular spacecraft utilized cloud detection and onboard feature techniques to redirect following observations towards the identification of areas exhibiting change or of particular significance. The IPEX mission used autonomous methods for picture gathering and data processing throughout the downlink procedure. The commanding approach of the ASTERIA spacecraft has recently undergone a metamorphosis. Additionally, it successfully showed the capability of determining its own orbit via passive imaging while operating in LEO, all without relying on GPS technology.

The Planner/Scheduler (PS) assumes the role of the principal controlling interface to the Remote Agent, functioning at the furthest level [9]. The PS software effectively manages a vast database that encompasses mission objectives and profiles over a significant duration, perhaps comprising the entirety of the operation's lifecycle. Throughout the duration of a mission, the executive consistently use the PS to create a coordinated network of activities at a strategic level, referred to as the plan. This plan is developed for each specific short-term scheduling period that the mission profile is divided into. In general, the temporal extent of each short-term horizon encompasses a significant number of days. When the PS receives a request from the Executive System (EXEC), it assesses the forthcoming scheduling horizon. The goals that are pertinent to the given horizon are subsequently extracted from the mission profile. PS integrates the initial spacecraft condition provided by the EXEC with an imperfect initial plan, resulting in the generation of a comprehensive and complete plan.

The proposed plan is sent by the PS to the Executive (EXEC) for implementation. In the context of RAX, Phase Two, the mission profile will include a duration of six days, consisting of two distinct scheduling windows, each spanning a period of three days. The RAX framework enables the declaration of two distinct types of objectives. The frequency and length of the “optical navigation windows” are determined to specify the specific time intervals during which the spacecraft is instructed to capture a series of asteroid images. These images are then used by the on-board Navigator for orbit determination purposes. The second form of goal involves specifying a “mini-sequence”, which refers to a collection of lower-level instructions that the EXEC system will send to the real-time program. Additionally, this type of goal includes criteria for activating the mini-sequence, taking into account certain synchronization limitations in relation to other scheduled operations. There are two scenarios in which a fresh plan will be required from MM/PS.

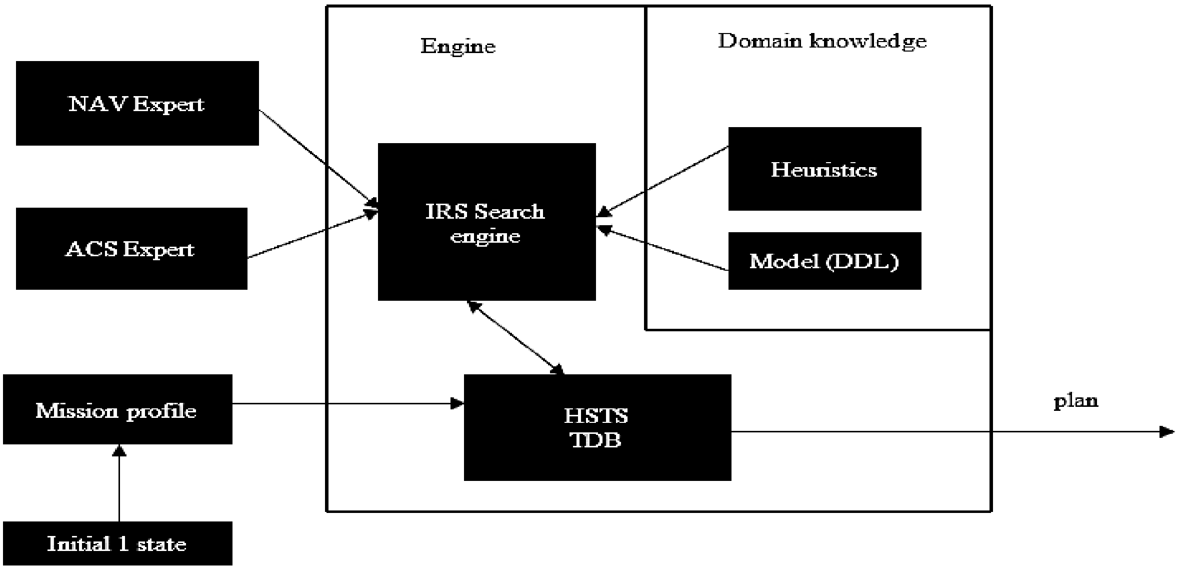

Fig 3. Planner/Scheduler Architecture.

The nominal operations include the execution of the activity Planner_Plan_Next_Horizon, which occurs at the conclusion of the existing scheduling horizon. The initiation of a formal request for a new strategic plan will be undertaken by the Executive Committee (EXEC). This request aims to designate the newly established initial state as the projected final state that will arise from the current implementation of the plan. This will enable the smooth integration of the previous and updated timetable without any disruption to its implementation.

Fault response: In the event that the fault protection system identifies an irregularity that might hinder the successful execution of upcoming tasks within the plan, the EXEC module will initiate a request for a fresh plan in order to restore normal operations. This action will be executed subsequent to verifying that the spacecraft has entered a stable and secure standby condition. In this particular case, the starting state refers to the standby responsibilities that have been allocated to each subsystem as depicted in the plan. Additionally, it includes health data that characterizes potentially deteriorated modes for subsystems that have had failures.

The system known as PS incorporates a heuristic search engine known as the IRS (Incremental Refinement Scheduler), which functions within the domain of partial or incomplete plans. The use of a temporal database is employed by the planner due to the explicit representation of time in a quantitative or metric manner inside the plans. Similar to other causal planners, the PS begins with an initial plan that is not fully developed and endeavors to enhance its completeness by including more database constraints. The constraints are derived from the objectives and constraint templates that are contained in a model of the spacecraft. The HSTS system offers the temporal database and the necessary tools for identifying and retrieving model data throughout the search process [10]. **Fig. 3** illustrates the architecture of the PS system.

Small-Body Proximity Operations

Conducting operations near and on little celestial bodies has been notably laborious and arduous. Thus far, an only five missions have attempted to function for prolonged durations in close vicinity to tiny celestial bodies. Hayabusa and Hayabusa2 (refer to **Fig. 4**)

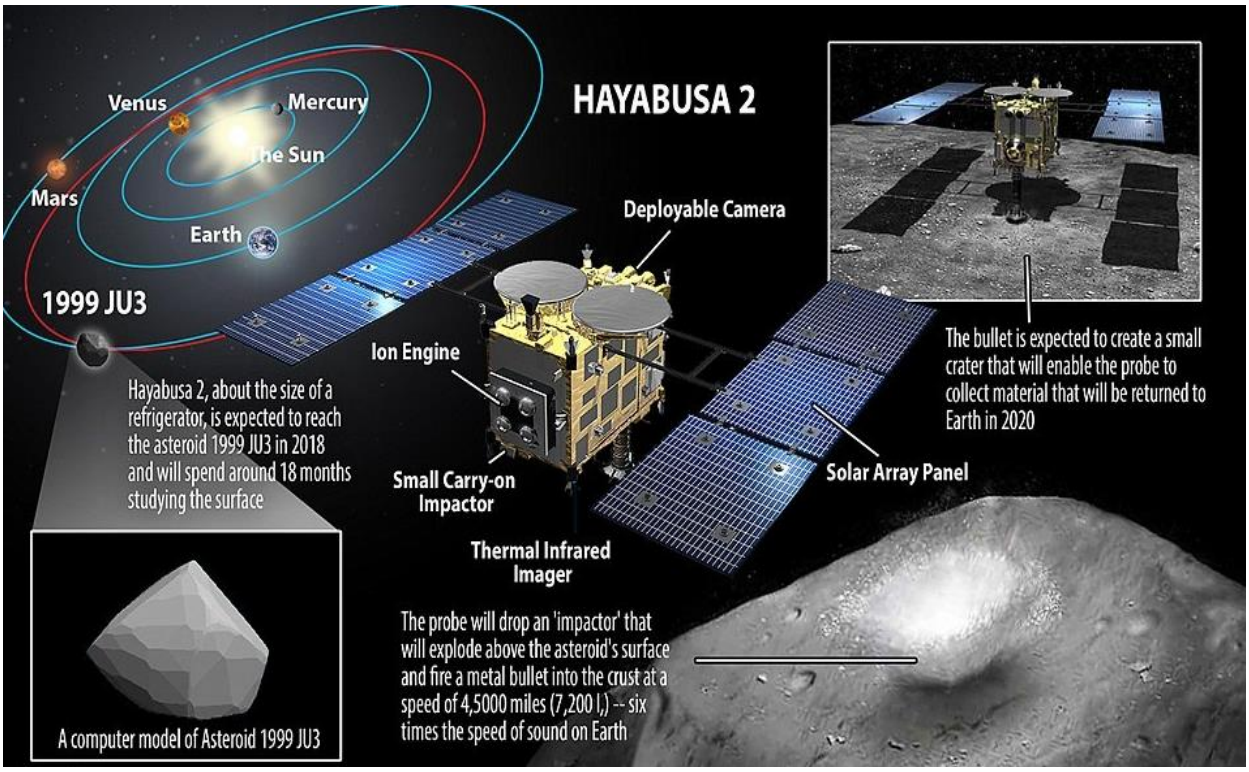

Fig 4. Illustration and Overview of The Hayabusa2 Project.

The initial acquisition of an asteroid sample from the Itokawa S-type near-Earth Asteroid 25143 by Hayabusa mission, executed by the JAXA (Japan Aerospace Exploration Agency) [11], occurred in 2010, marking a span of six years since this event took place. Significant progress has been made in the analysis of surface regolith constituents and the understanding of processes of planetary surface, such as thermal evolution inside parent bodies, the chronology of Itokawa and space weathering. Currently, there exist two active sample return missions, specifically NASA's OSIRIS-Rex and JAXA's Hayabusa2. These missions are now in transit towards their respective target bodies, which are B-type 101955 Bennu and C-type 162173 Ryugu.

The Hayabusa mission successfully showcased various technological advancements for the retrieval of samples from near-Earth asteroids. The progress made in this field involved the adoption of ion engines as the main propulsion means, the incorporation of optical navigation methods to achieve accurate asteroid approach and landing, the implementation of sample collection procedures in microgravity environments, and the successful reentry of the sample capsule into the Earth's atmosphere at high velocities. The collected samples have been systematically classified by the use of energy-dispersive X-ray spectroscopy (EDS) [12], scanning electron microscopy (SEM) [13], and optical microscopy [14]. The Hayabusa2 mission, conducted by the JAXA, is the second endeavor to retrieve samples from an asteroid. The spacecraft is now in route to its destination, the asteroid 162173 Ryugu, which falls under the C-type classification. This particular type is characterized by its abundance of volatile elements and carbonaceous composition. The spacecraft is equipped with a research lander known as Micro-Asteroid Surface Scout(MASCOT), which is designed to undertake in-situ measuments on the surface of asteroids [15]. Scientific measurements will be undertaken on a world scale using remote sensing techniques, on a local scale using surface landers, and on a microscale via the examination of collected samples.

In their study, Matsumoto, Hasegawa, Nakao, Sakai, and Yurimoto [16] conducted an analysis of micron-scale particles retrieved from the surface of Itokawa asteroid by the Hayabusa mission. Through an examination of surface textures and chemical compositions, the researchers identified novel microstructures present on these particles. The researchers observed the presence of splash melts, surface blistering, and a multitude of microscopic adhering particles on the samples collected from Itokawa. In order to examine the nature and origin of the particles, as well as the effect of micrometeoroid impacts on the surface of Itokawa, a total of seven focused ion beam sections were retrieved. The research findings indicate that the regolith of the asteroid Itokawa has undergone modifications as a result of collisions from micrometeoroids. There is a growing interest in volatile-rich carbonaceous meteorites for upcoming missions such as OSIRIS-REx and Hayabusa2.

In their study, Keil [17] conducted laboratory experiments to effectively comprehend the thermal modification processes of asteroids that include high amounts of volatile substances. The researchers saw a substantial reduction in mass and observed comparable patterns of mass loss when the samples were heated to temperatures of 1000°C. This mass loss was attributed to the removal of water and hydroxyl groups from the abundant phyllosilicates and Fe-(oxy)hydroxides present in the samples. Cincinelli, Pieri, Zhang, Seed, and Jones [18] devised an innovative approach that included the use of gas combustion, and chromatography to ascertain the compound-specific nitrogen isotope compositions derived from thermally altered carbonaceous chondrites found in Antarctica. The authors propose that the carbonaceous chondrite samples serve as suitable representations for the Hayabusa2 mission's target asteroid, Ryugu [19]. Ryugu is classified as a C-type asteroid and is believed to consist of diverse components, including both hydrated and dehydrated minerals.

Infrared spectroscopy has been used in several missions like as Hayabusa, Hayabusa2, OSIRIS-REx, and others, with the purpose of examining surface mineralogy, silicate hydration, and organic compounds. Nevertheless, prior studies have been streamlined in order to extrapolate their conclusions to actual observations. In a study conducted by Maturilli, Helbert, and D'Amore [20], the authors established and managed the Planetary Emissivity Laboratory (PEL) at the German Aerospace Center (GAC). The researchers also provided evidence that demonstrates the relationship between the angle of emergence and laboratory-measured emissivity spectra. Furthermore, the researchers have generated a unique database consisting of emissivity and reflectance spectra of asteroid analogues that were measured under vacuum factors. Remote X-ray spectroscopy is a prominent instrumental method used in missions to celestial planets. In their study, Branduardi-Raymont et al. [21] introduced advanced X-ray optics designed for remote planetary X-ray imaging spectrometry. This technological development has the potential to importantly expand the scope of discoveries in planetary science and contribute to a deeper comprehension of the characteristics and origins of many planetary entities.

The primary emphasis of Tsuda [22] is in the examination of the inception and development of the early solar system, and the potentials of forthcoming missions targeting carbonaceous-type asteroids rich in volatile elements, such as OSIRIS-REx and Hayabusa2. These activities serve as sources of incentive for the pursuit of new missions to primitive bodies that have not yet been explored. As a result, NASA has chosen the Psyche mission, which involves a rendezvous with a metallic core, and the Lucy project, which entails several flybys of Trojan asteroids. Operating in the vicinity of minor celestial bodies presents several challenges. These challenges include the presence of microgravity, the potential for debris to be ejected from their surfaces, the uneven topography of these bodies leading to the formation of sharp shadows and occlusions, as well as the unrestricted surface characteristics of these bodies. The challenges associated in reaching the surface, gathering samples, and safely bringing them back are mostly attributed to the uncertainties inherent in the unfamiliar environment and the complex interplay with a celestial body characterized by low gravity. The problems pertaining to the deployment and accessibility of the Hayabusa's MINERVAs surface [23] and Rosetta's Philae [24] serve to emphasize some aspects, while also shedding light on our restricted understanding of the surface characteristics, as shown by OSIRIS-REx [25]. Due to the inherent ambiguity surrounding such information, trips to minor celestial worlds often need a certain level of autonomy.

III. ADVANCES IN LANDED MISSIONS: FROM MARS TO THE MOON AND BEYOND

Landed Missions

During the entry, descent, and landing (EDL) phase on Mars, the execution of commands and the management of control systems are limited to autonomous operations, mostly as a result of the communication latency and associated limitations. The process of landing on Mars presents significant challenges due to its sparse atmosphere and the need of decelerating to a nearly stationary fall speed using a limited fuel supply. This necessitates the use of guided entry techniques to achieve deceleration velocities that allow for the efficient utilization of parachutes. The presence of wind during the descent of a spacecraft introduces uncertainties in the behavior of parachutes, mostly owing to the lateral velocity imparted to the falling object.

The Chang'e 4 lunar mission [26], which transported the Yutu-2 rover, successfully highlighted the capability of achieving precise autonomous landing in intricate topography on the moon's far side (see to **Fig. 5**). The spacecraft used terrain relative navigation, together with hazard assessment and avoidance techniques, to successfully achieve a landing in a situation when radiometric data was unavailable. The Chang'e-4 (CE-4) project, undertaken by China, is the inaugural attempt to deploy a manned lander and rover on the hitherto uncharted moon's far side. The probe is comprised of three components: the Queqiao, a rover and a lander relay satellite. The Queqiao satellite was effectively deployed on May 21, 2018, and subsequently attained insertion into the halo orbit encircling the L2 Lagrange point on June 14th. Queqiao's remarkable accomplishment solidified its status as the inaugural satellite to successfully establish communications between the Earth and the hitherto unexplored far Moon's side. On December 8, 2018, the lander with the Yutu-2 rover was successfully deployed and landed within the Von Kármán crater, precisely at coordinates 45.5° S and 177.6° E, in accordance with the predetermined plan [27]. It happened exactly at 10:26 (UTC+8) January 3, 2019.

There were nine scientific equipment CE-4 on-board probe. The lander is equipped with four instruments, including low-frequency radio spectrometer [28], the landing camera [29], terrain camera [30], and lunar lander neutrons and dosimetry [31], which has been provided by germany. The rover is equipped with four instruments, namely the advanced small analyzer for neutrals [32], the panoramic camera [33], lunar penetrating radar [34], and visible and near-infrared imaging spectrometer [35], which has been contributed by sweden. the ownership of the netherlands-china low-frequency explorer [36] is attributed to the relay satellite. In summary, the primary science goals of CE-4 mission consist of three aspects. Firstly, it aims to conduct observations in the low-frequency radio-astronomical areas [37]. Additionally, the main reason of this study is to interpret the mineral compositions, and geomorphology structure of the specified roving locations. Finally, the objective is to identify and examine the Earth-Moon space habitat, with a particular focus on the lunar far side area. As of 1st February, 2020, the lunar rover CE-4 has effectively finished 14 scientific inquiry lunar days following a year of operational engagement [38].

Apart from the successful landings on Mars and the Moon, several missions have independently made contact with the surfaces of minor celestial bodies. The Hayabusa mission in 2005 showcased the ability to autonomously descend the last 50 meters onto a nearby surface target for the purpose of collecting samples. This was achieved by the use of laser ranging, which allowed for adjustments in both height and attitude at distances less than 100 meters [39]. The aforementioned capacity was also used during the Hayabusa2 mission in 2019. In this mission, an onboard terminal-descent/ hybrid ground technique was implemented, whereby the ground control system managed the boresight strategy, while the onboard model oversaw the lateral motion during the last 50 meters. The use of terrain-relative navigation was employed by the OSIRIS-REx mission in the year 2020 during its go-and-touch maneuver executed for the purpose of sample collecting [40]. By employing a shape-model derived from ground-based data, the spacecraft successfully correlated natural characteristics with the image representations obtained from the produced model, so enabling it to approach the celestial body for the purpose of conducting a touch-and-go sampling maneuver. The aforementioned portion was carried out in an independent manner, but under the supervision and guidance of ground personnel.

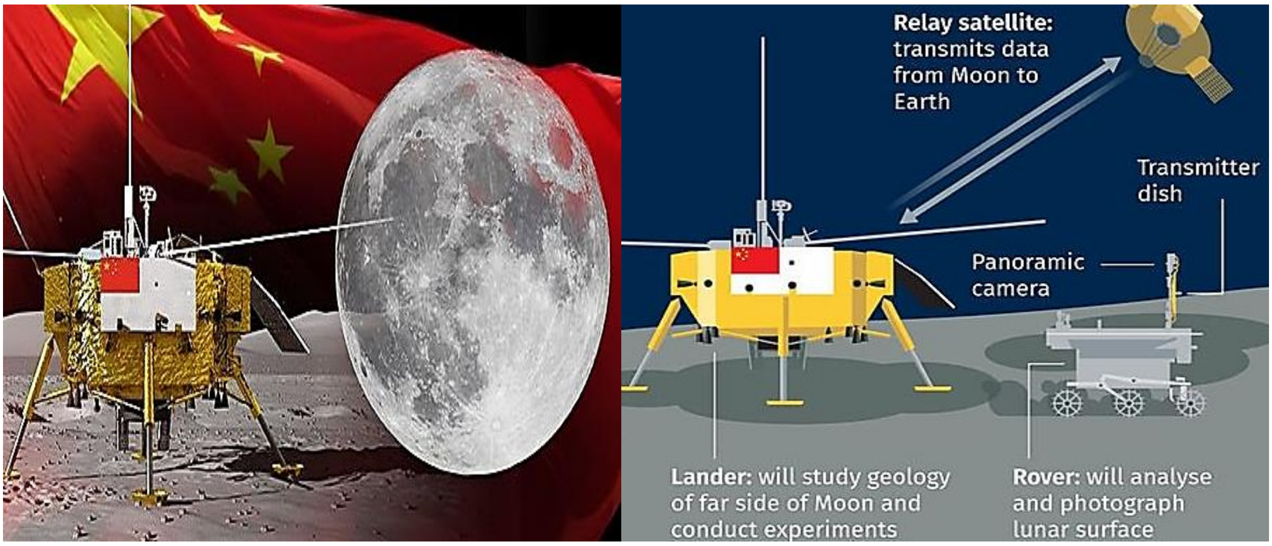

Fig 5. Chang'e 4 Lunar Mission Design.

Surface Missions

In scientific exploration, the deployment and sampling activities of instruments often need direct touch and interaction with the surface. The Mars Exploration Rovers successfully demonstrated their ability to autonomously approach a target and accurately set instruments on it, even when the target was picked from a distance of several meters. The acquisition of samples from the asteroid Bennu surface which was successfully carried out by the OSIRIS-REx mission, employing a touch-and-go operation facilitated by its 3.4-meter extended robotic arm. This involved drilling through the surface to a depth of about 50 cm below what was expected for collecting samples. The mission objective for the NASA's OSIRIS-REx was to learn and take samples from asteroid 101955 Bennu, which is primarily made of carbonaceous materials. It is believed that the material, expected by the end of 2023, will help scientists gain a better comprehension of how the solar system was formed and developed [41].

The main purpose of this study is to give insights into the first phases of planetary formation and the origins of organic molecules, which played a crucial role in the development of life on Earth. Following the completion of the primary objective, the spacecraft is planned to perform a flyby maneuver on asteroid 99942 Apophis, designated as OSIRIS-APEX. The OSIRIS-REx spacecraft, as depicted in **Fig. 6**, was effectively launched on September 8, 2016 [42]. Following its launch, the spacecraft successfully executed a flyby of Earth on September 22, 2017, and subsequently arrived at its designated target, the asteroid Bennu, on December 3, 2018.The subsequent two years were allocated to the examination of the surface with the aim of determining a suitable site for the retrieval of a sample. On 20th October, 2020, the OSIRIS-REx spacecraft effectively performed a controlled descent onto the astronomical object named Bennu, therefore achieving the objective of collecting a sample [43]. On May 10, 2021, the OSIRIS-REx spacecraft completed its mission at the asteroid Bennu and effectively transported its acquired sample to Earth on September 24, 2023 [44].

Subsequent to this notable accomplishment, the spacecraft embarked on its protracted journey to scrutinize the attributes of 99942 Apophis. The spacecraft is anticipated to arrive at Apophis in April 2029 [45]. The rationale behind choosing Bennu as the object of study is its classification as a “time capsule” that originated during the first phases of the creation of the Solar System. Bennu exhibits a conspicuously low albedo, implying a dim surface, and is classified as a B-type asteroid, belonging to the carbonaceous C-type asteroid cluster. The asteroids under consideration are categorized as primitive owing to their limited geological modifications after their initial formation. The selection of Bennu as the target of study was primarily based on its abundance of pure carbonaceous material. This material is of great significance since it contains essential organic molecules required for life and also represents materials that predates the origin of Earth. The presence of organic compounds, like as amino acids, has been detected in samples obtained from meteorites and comets, suggesting that some essential components for life may undergo spontaneous synthesis in extraterrestrial environments.

The estimated expenditure for the OSIRIS-REx mission is around $800 million, except the Atlas V launch vehicle, which amounts to approximately $183.5 million. The extended mission of OSIRIS-APEX incurs an extra expenditure of US$200 million. This is the third planetary scientific mission that has been chosen as part of the New Frontiers program, after the missions of Juno and New Horizons. The principle investigator, Dante Lauretta, assumed the role in 2011 subsequent to the first lead investigator. He is affiliated with the University of Arizona. Regrettably, Michael Julian Drake's demise occurred a little four months subsequent to the mission's endorsement by NASA [46] The OSIRIS-REx mission marked a significant milestone as the first US spacecraft to successfully retrieve samples from an asteroid. The past instances of asteroid missions include the Japanese spacecraft Hayabusa, which conducted a visit to 25143 Itokawa in 2010, and Hayabusa2, which embarked on a mission to 162173 Ryugu in June 2018.

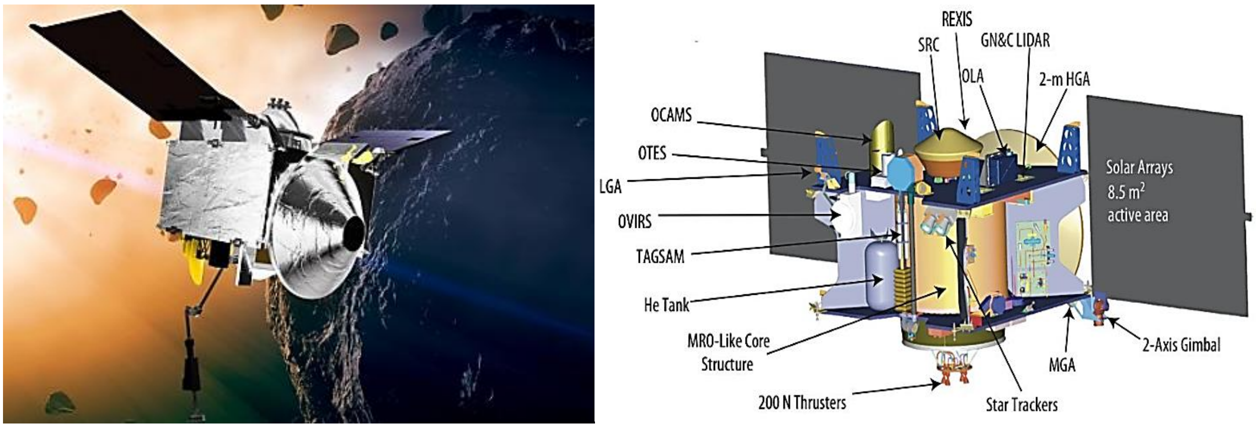

Fig 6. OSIRIS-REx Spacecraft Design.

The inclusion of surface mobility significantly enhances the overall worth of a landed mission as it facilitates the ability to establish contact and engage with a more extensive region of the planetary surface. In order to provide secure surface movement, each Mars rover mission has included a kind of autonomous surface navigation. The Mars Pathfinder mission in 1997 showcased the autonomous obstacle avoidance capabilities of the Sojourner rover. This was achieved by the use of laser striping in conjunction with a camera, which enabled the detection of untraversable rocks, also known as positive geometric hazards. Subsequently, the autonomous system used a bang-bang control mechanism for its brushed motors, enabling it to navigate and circumvent any obstacles in order to successfully attain its predetermined objective. The Mars Exploration Rovers, namely Opportunity and Spirit, together with the Mars Science Laboratory Curiosity rover, used an advanced autonomous navigation algorithm that relied on dense stereo mapping from their cameras located on the body and mast [47]. The algorithm was employed to assess possible threats in the terrain. The algorithms employed in this research were tasked with the manipulation of three-dimensional point clouds, converting them into a grid-based representation. The algorithms successfully estimated a range of terrain parameters, including slope, height differences, and roughness, for each unique segment of terrain covered by the rover.

The Mars 2020 Perseverance rover use a sophisticated algorithm to evaluate and select a safe course for its traverse. The use of specialized Field-Programmable Gate Arrays (FPGAs) [48] enhances the stereo sensing capabilities and substantially accelerates the processing of data. These FPGAs are specifically designed to analyze the tracks of the wheels as they traverse the ground, enabling an assessment of the terrain's traversability. In the field of route planning, the evaluation of possible collision between the terrain and the rover’s body is a crucial aspect for determining the optimal placement of a passively articulated suspension system. This task requires extensive computing calculations. In order to alleviate the computational strain, a cautious approximation technique is employed. This approximation method streamlines the computational process while also assuring the preservation of a collision-free route that assures safety. Moreover, a thorough evaluation is undertaken to determine the most suitable course of action by taking into account orbital and previously recorded rover information, in addition to assessing the rover's traversal throughout the nearby terrain.

The Mars rovers have independently covered lengths of several hundred meters, beyond the visual range of imaging used by ground operators, sometimes referred to as over the horizon driving. During a designated period of time spanning a weekend, the Opportunity rover successfully traversed a distance of 200 meters via the implementation of a multi-sol autonomous driving sequence.

IV. FUTURE SCOPE FOR AUTONOMY AND AUTONOMOUS SMALL BODY EXPLORER

Autonomy

This serves as a preliminary indication of what is expected. Current mission research projects and concept studies are actively engaged in the examination of various robotic systems designed to investigate the surfaces of celestial planets beyond Earth. One of the proposed methods for sample collection and analysis on Europa's surface involves the use of robotic arms. A rotorcraft successfully conducted many powered flights inside the tenuous atmosphere of Mars, while another substantial rotorcraft is now under construction with the purpose of investigating the surface of Titan, taking advantage of its dense atmosphere. Research is now being conducted on the exploration of the seas of icy celestial bodies using probes [49, 50]. These probes aim to navigate through extensive layers of cryogenic ice or maneuver through the vents and crevasses found in Enceladus' tiger stripes, which are known for the plumes seen in the moon's southern portion. Extensive research is now being conducted on lunar rovers with the aim of enabling them to traverse vast distances, spanning hundreds of kilometers, in order to study diverse areas located in close proximity to the lunar equator, as well as in the polar regions.

The future generation of explorers, characterized by their growing wealth of capabilities, will necessitate a heightened level of autonomy. This is especially true for remote destinations and ocean worlds, where the surfaces of target bodies remain unexplored and where communication and power resources are more limited compared to the Moon and Mars. Although explorers of this kind may exhibit a variety of characteristics, it is plausible that there are fundamental aspects of autonomy that are often observed throughout these platforms. The advancement of these fundamental features is crucial in facilitating the successful execution of complicated tasks by robotic systems, even in the face of little information and significant uncertainty inside the challenging areas they are designed to investigate.

In light of the aforementioned challenges, what strategies may be used to facilitate significant progress in the advancement of autonomy? To address this challenge, it is fundamental to examine the primary deficiency, which involves the consistent functioning within a partly familiar and hostile setting, while also accounting for unavoidable system deteriorations. The aforementioned statement would facilitate the development of essential function- and system-level autonomous skills within an integrated framework, primarily designed to effectively address a variety of circumstances. Several autonomy problems were documented at a NASA Autonomy Workshop launched by the Science Mission Directorate [51].

Autonomous Small Body Explorer

An instance that may present a suitably demanding prospect for the progression of robotics and autonomous systems involves the utilization of a cost-effective SmallSat, which refers to a spacecraft weighing less than 180 kg and adhering to standardized format conditions at smaller dimensions (e.g., 12U and 6U). This SmallSat would be deployed to autonomously journey towards, approach, land on, and function on the surface of a NEO (near-Earth object) [52]. The SmallSat is intended to be built in a manner that enables its functioning to be guided by overarching objectives established on the ground, hence facilitating effective operational supervision. The following section is a compilation of often asked questions and their corresponding answers pertaining to the aforementioned idea.

What factors contribute to the significance of NEOs in the context of exploration? The investigation of NEOs has significance across four key domains: planetary defense, human exploration, in situ resource usage, and scientific research. For instance, Hayabusa2, Hayabusa, and the preceding missions were mostly oriented towards scientific objectives. During that period, their operational capabilities were mostly grounded and hence restricted in terms of surface operations. We propose the application of autonomous robotic technology for the purpose of accessing the surfaces of NEOs. This advancement builds upon previous achievements and has significant promise for facilitating access to more distant celestial bodies, including trans-Neptunian, comets, centaurs, asteroids substances, and objects inside the Kuiper belt. Small celestial objects are plentiful and exhibit a wide range of composition and origin. They are distributed throughout the solar system, extending all the way to the Oort Cloud [53].

What factors make NEOs particularly suitable for the advancement of autonomy? Near-Earth Objects (NEOs) include a multitude of obstacles that are characteristic of very distant and austere locations, but they remain within reach of SmallSats. Due to the wide range of variations among celestial bodies, the specific characteristics of their surroundings are often not well understood in advance. Consequently, the behaviors of spacecraft near or upon their surfaces would be highly dynamic due to the influence of microgravity. Moreover, the replication of such a mission inside a terrestrial analog habitat poses significant challenges, and the effectiveness of modeling is constrained by the unknown attributes of the habitat that will be encountered.

What is the significance of autonomy in empowering small entities? The use of autonomy has the potential to enhance accessibility by mitigating operational expenses and facilitating the investigation of a wider range of environments compared to the existing ground-in-the-loop exploration approach. The integration of onboard situational awareness in autonomous systems enables enhanced proximity operations, including closer flybys and more advanced maneuvers. Moreover, it ensures the safe execution of landing and relocation processes on the surface. The need for autonomy arises while operating in close proximity to, on, or inside celestial bodies due to their mostly unexplored and very challenging terrains, as well as the ever-changing dynamics involved in the spacecraft-body interaction. Missions like as Hayabusa and Hayabusa2, which included the deployment of surface assets, mostly relied on ground-based operations and had limited surface operating capabilities throughout their respective missions.

The successful execution of approaching, landing, and reaching selected destinations on a NEO necessitates the use of advanced technologies in the fields of surface mobility, compact spacecraft, computer vision, and machine learning. During the approach phase of an autonomous mission, the spacecraft would use its onboard sensor capabilities, processing power, and algorithms to develop estimations of various parameters of the celestial body. These parameters include the local surface topography, rotation rate, gravity model, form, rotation axis, and potential safe landing locations. It is fundamental to note that missions would operate with minimal previous knowledge of the body. The use of an onboard system offers the benefit of increased picture capture rates, which becomes favorable for computer vision algorithms.

Moreover, this approach leads to a substantial decrease in the size of the operations crew, in contrast to ground operations that are constrained by restricted communication bandwidth. Machine learning(ML) has the potential to effectively encode intricate models and effectively manage significant uncertainties. For instance, it can successfully recognize and track body-surface landmarks amidst substantial variations in size and lighting conditions across extensive distances, spanning tens of thousands of kilometers. Moreover, ML algorithms would effectively manage intricate, and the geo-physical characteristics of which are not known in advance, hence facilitating efficient mobility and manipulation. Once this autonomous capacity is developed, it would have wider applicability to planetary entities that have unknown motions/rotations, topographies, and perhaps existing atmosphere conditions.

This particular situation exhibits distinct success measures for every step of escalating complexity. During the first step, trajectory correction maneuvers are used to direct the spacecraft towards the approach point, which is the location where the target becomes noticeable in the camera's restricted sector of view. The target, albeit appearing as a point-spread function of subpixel size, may be seen via the camera. The second step is a very demanding stage that requires achieving a critical point of stability at a secure distance, after establishing the essential characteristics of the body (such as trajectory, rotation, and form). The third step would include the meticulous process of selecting an appropriate landing location, implementing effective guiding systems, and executing a safe touchdown. The last step and measure of success would include the capacity to move over the surface and reach specific areas, as well as modify the shallow regolith surface in order to get measurements. The execution of all activities would be carried out autonomously, with a focus on achieving objectives established by ground operators and scientists. The last success measure pertains to the retrieval of essential data for the purpose of tracking and analyzing the decision-making processes carried out by the spacecraft during its mission.

Promising results were obtained from a previous investigation that examined the accessibility and practicality of the aforementioned scenario. In order to enhance ease of surface access, the spacecraft is engineered to possess the capability of self-righting and functioning from any stable condition. This allows it to do hopping and tumbling maneuvers like to those seen in parabolic flight experiments. Upon reaching the surface, a finite lifespan is assumed in order to mitigate the limitations imposed by the use of extensive deployable solar panels. Micro-thrusters provide the capability to not only facilitate spaceship guidance during the landing process but also enable the relocation of the platform to various locations on the celestial body. The development of miniaturized manipulators specifically designed for CubeSats has the potential to facilitate the manipulation of surfaces for various purposes such as sampling and conducting measurements. This scenario has the potential to be expanded to include missions involving several spacecraft.

Furthermore, the advancement of the aforementioned functions would necessitate the evolution of an architectural framework that effectively combines function- and system-level components. This integration would facilitate the interaction of cross-domain models at appropriate fidelity levels, thereby enabling the successful execution of complex missions. It is imperative that this architecture incorporates mechanisms for ground oversight and the ability to retry operations when necessary. The cost-effectiveness of this technological demonstration enables a more assertive approach to risk-taking, leading to significant advancements in autonomous robotic capabilities. The widespread availability of architecture and algorithms will reduce the barriers to entry for universities, hence creating more options for the deployment of SmallSat missions to a variety of Near-Earth Objects (NEOs).

V. CONCLUSION

This paper provides a discussion of the effects of autonomous robotic capabilities on space missions, with a specific emphasis on the role of robots in surface exploration missions conducted on Mars. Previous missions have successfully used a robotic arm to facilitate tasks like as the identification and analysis of water ice deposits, geological investigation, and the deployment of European sensors on the surface of Mars. The Deep Space I mission, conducted in 1999, showcased the implementation of goal-oriented tasks via the use of onboard planning and execution mechanisms. Similarly, the Stardust mission successfully completed a flyby maneuver and proved the capability of self-guided navigation maneuvers. The Deep Impact mission, conducted between 2005 and 2010, effectively implemented a self-guided terminal navigation maneuver lasting two hours, while also monitoring the trajectories of two comets.

Autonomy has also been used to enhance the operational capabilities of Earth-orbiting missions, like the Earth-Observing-1 spacecraft, in the realm of scientific endeavors. The IPEX mission employed autonomous methodologies for the processing of data and the capture of images. The control system of the ASTERIA spacecraft has just undergone a transformation. The shift in control mechanisms has involved a change from employing time-based sequences to utilizing task networks. In addition, the spacecraft autonomously establishes its orbital trajectory through the utilization of passive imaging techniques during its operation within Low Earth Orbit (LEO). The Planner/Scheduler (PS) assumes the role of the primary controlling interface to the RemoteAgent, operating at the highest level. The PS program is tasked with the management and upkeep of a comprehensive database that encompasses mission objectives and profiles. Furthermore, the program employs the Planning System (PS) in order to construct a synchronized network of top-level activities within certain short-term scheduling timeframes.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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