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Sampling, Mobility, and Anchoring in Small-Body Sampling Robots: A Comprehensive Review

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ABSTRACT

Small-body sampling robots are crucial for asteroid and comet exploration as well as in situ resource utilization, yet they face unique challenges of microgravity, irregular terrain, and uncertain surface properties. Although existing studies have advanced sampling, mobility, and anchoring technologies, current reviews often treat these technologies in isolation, failing to reveal their intrinsic coupling relationships and hinder holistic research and development. To address this gap, this review provides a unified review of small-body sampling robots, focusing on the mechanical aspects of the three core functional modules: sampling, mobility, and anchoring. It surveys state-of-the-art techniques demonstrated in missions, highlights emerging approaches and compares performance trade-offs in efficiency, adaptability, and technology readiness. The review further highlights critical challenges, including the coupling effects among the three functional modules as well as additional challenges arising from other factors. Finally, this review outlines the prospective development trends of small-body sampling robots. By consolidating lessons from past missions and emerging innovations, this work aims to serve as both a reference for ongoing research and a road map for the design of next-generation autonomous sampling robots.

1 | Introduction

The accelerating depletion of terrestrial mineral resources has raised significant concerns about the long-term sustainability of human civilization. According to the *2024 Statistical Review of World Energy* [1], global oil and natural gas reserves may last only about 50 years, whereas coal reserves could sustain roughly 130 years of consumption [2]. Additionally, the *2025 Global Mining Outlook* further highlights supply bottlenecks for critical minerals such as rare earth elements and gold [3].

In contrast, outer space offers vast, largely untapped resources that may far exceed those available on Earth [4]. The exploitation of extraterrestrial resources not only supports deep space exploration and off-Earth settlement but also presents a potential solution to terrestrial resource scarcity [5]. Based on the celestial body type and environmental characteristics, space resources are generally classified into three categories: near-Earth object (NEO) resources, deep space resources, and orbital environment resources. NEO resources, particularly from asteroids, have attracted considerable attention owing to their compositional diversity and relative accessibility. For instance, M-type asteroids are enriched in platinum-group metals (PGMs), with concentrations reaching up to several thousand times those of Earth's crust [6]. NASA's *Psyche* mission targets 16 Psyche, an M-type asteroid estimated to contain over 500 million tons of iron and 50 million tons of nickel, with an overall economic value exceeding $10 trillion [7, 8]. Such metallic-rich bodies could significantly alleviate the supply chain pressure for critical materials [9]. Deep space resources, such as those potentially present on Jupiter's moon Europa, offer another promising avenue. Europa is believed to host a subsurface ocean containing more water than all of Earth's oceans combined [10, 11]. The presence of dissolved salts and hydrothermal activity driven by tidal heating suggests the potential for sulfide mineral deposits—critical for both resource development and astrobiological investigations [12, 13]. A one-square-kilometer solar array could generate nearly 1 TW of electricity per year, which is enough to replace conventional ground-based power plants [14]. Among various extraterrestrial bodies, small bodies (including asteroids and comets) are not only ubiquitous within the solar system but also possess substantial scientific and economic potential. According to the Asterank database, 997 well-characterized asteroids have been evaluated, with 701 of them estimated to be worth more than $100 trillion [15]. For example, 16 *Psyche* is believed to contain hundreds of millions of tons of rare metals in addition to its iron and nickel reserves [7, 9].

Despite their substantial potential, small bodies present significant challenges due to their low gravity, high vacuum conditions, and irregular surface topography [16]. Current exploration efforts primarily rely on flybys and orbital missions, which provide only limited data such as size, mass, and crater morphology. Comprehensive in situ scientific analysis remains largely out of reach, and the field of space mining is still at an early stage of development. Robotic explorers capable of sustained and repeated surface operations are key to obtain detailed and continuous data on small bodies. However, unlike large planetary bodies, asteroids and comets are characterized by low mass and weak gravity, resulting in low escape velocities. Their surfaces are often covered with boulders, regolith, and rubble piles, making stable attachment and operation extremely challenging for robotic systems.

Although numerous missions have advanced our understanding of small-body exploration, existing reviews remain fragmented—typically focusing on either sampling or mobility though neglecting their interdependence [17, 18]. Anchoring technologies, despite their critical role in stabilizing surface operations, have received even less systematic attention, often only noted in the context of individual mission shortcomings [19, 20]. Wang et al. [21] summarized the research progress of small celestial body sampling robots, covering their current tasks, structural composition, and operational characteristics. However, they did not conduct extraction and coupling analysis of their key functions. With asteroids and comets gaining prominence both as scientific targets and potential resources, there is a pressing need for a comprehensive synthesis that bridges these three domains.

This review integrates sampling, mobility, and anchoring into a unified framework, which constitutes its primary contribution: overcoming the fragmented treatment in previous studies by establishing a systematic and integrated review of the three core modules, thereby elucidating their intrinsic interdependencies. Furthermore, this review offers a second key contribution by synthesizing past mission experiences, identifying unresolved technical challenges and outlining forward-looking pathways for future research and development.

The remainder of the paper is organized as follows: Section 2 introduces the research background from three perspectives: policy orientation, resource utilization strategies, and major sampling missions. Section 3 presents a comprehensive review of sampling, mobility, and anchoring technologies, covering both demonstrated achievements in past missions and concepts proposed for future applications. In Section 4, the key challenges faced by sampling robots under the extreme conditions of small bodies is analyzed. Section 5 outlines future technological development trends, whereas Section 6 concludes the review with a summary of insights and perspectives.

The overall research framework of this review is illustrated in the Figure 1, which highlights the key technologies and challenges discussed in subsequent sections.

2 | Overview of the Development of Small-Body Sampling

Since the beginning of the 21st century, space mining has emerged as a strategic approach for obtaining extraterrestrial resources. It has attracted significant attention from major spacefaring nations, including the United States, Europe, Japan, India, and Russia. These nations have initiated scientific exploration and in situ resource utilization (ISRU) programs targeting the Moon and asteroids, while also supporting commercial enterprises in developing space mining technologies.

2.1 | Policy Landscape

From a policy perspective, on November 25, 2015, then-U.S. President Barack Obama signed the *U.S. Commercial Space Launch Competitiveness Act*, which granted private enterprises the legal authority to engage in space mining and clarified property rights over extracted space resources [22]. Subsequently, on June 18, 2018, the United States announced the formal establishment of the U.S. Space Force, which became fully operational by early 2020. Luxembourg, a pioneer in space resource governance, launched a national initiative in 2016, which aimed at asteroid mining, particularly focusing on near-Earth objects (NEOs) [23]. The country also enacted legal frameworks to secure the ownership rights of private operators over resources extracted from celestial bodies. Collectively, these policy measures laid the groundwork for both governmental and commercial engagement in small-body exploration.

2.2 | Resource Utilization Strategies

Current approaches to extraterrestrial resource development are primarily categorized into two strategies: Return-to-Earth (RTE) [24] and ISRU [25]. As shown in Figure 2a,b, two widely adopted RTE strategies have been emerged in recent planetary exploration missions. The first is the touch-and-go (TAG) approach, which enables rapid acquisition of surface or shallow regolith samples through brief contact with the target body [26]. This method minimizes mission risk and has been successfully demonstrated by Japan's *Hayabusa* and *Hayabusa2* missions. The second strategy involves lander-based or rover-based sampling systems, exemplified by China's *Chang'E* missions [27]. These systems typically include landers or rovers who can perform extensive and

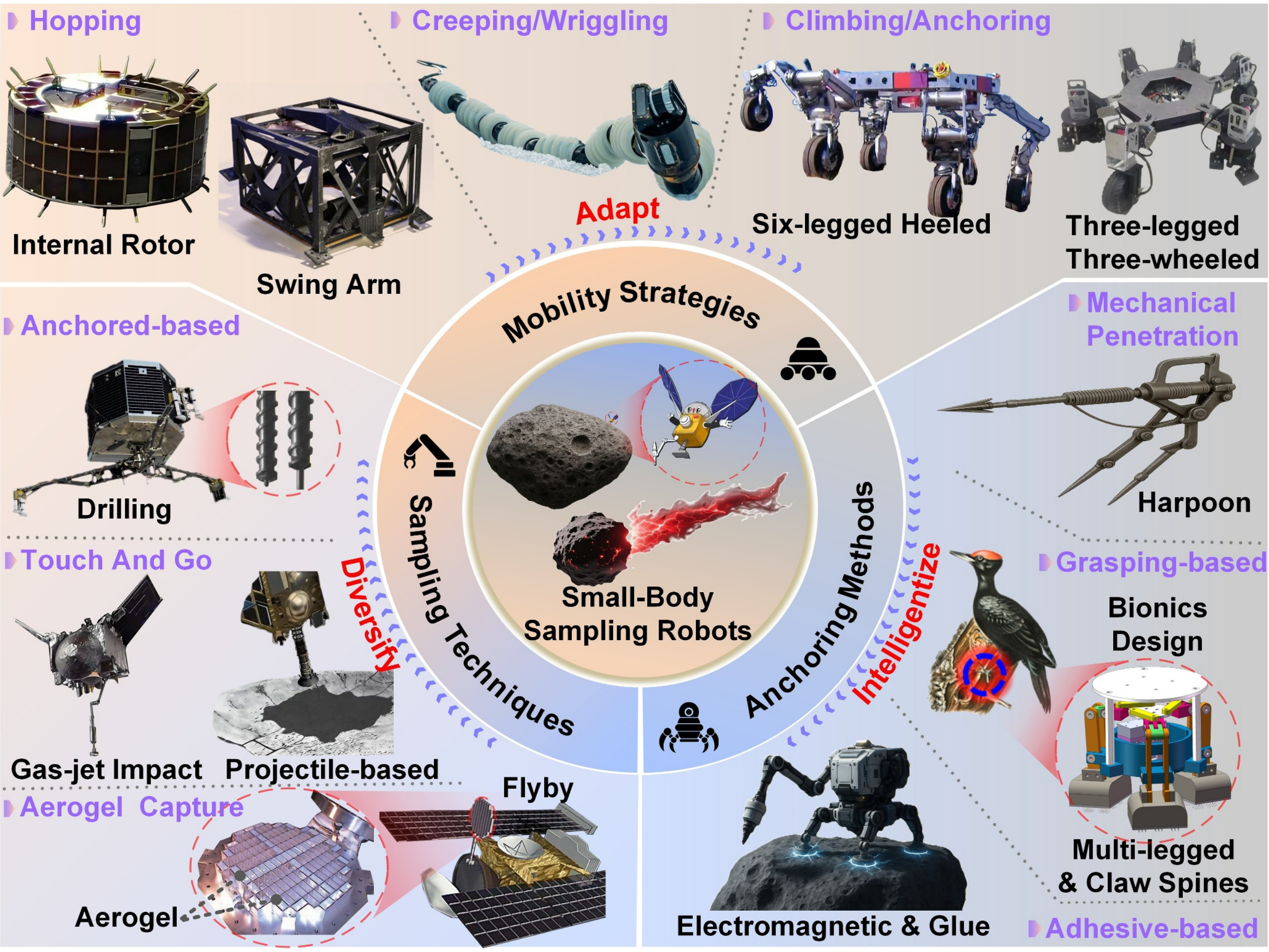

FIGURE 1 | Graphical abstract: Functional and structural taxonomy of small-body sampling robots.

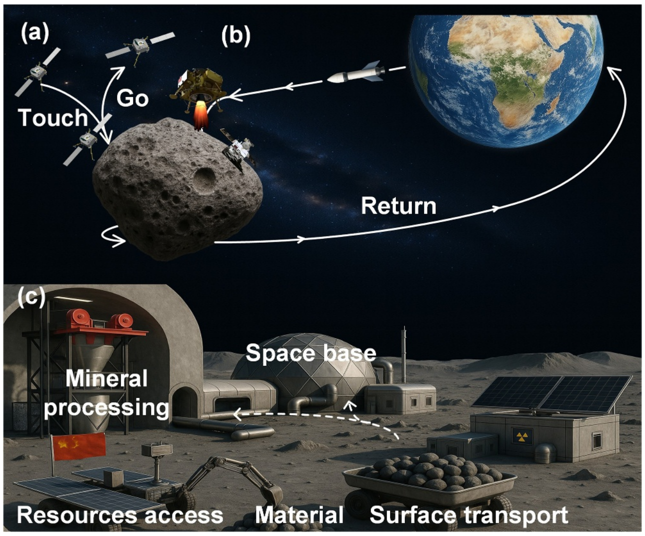

FIGURE 2 | Forms of space resource development. (a) TAG. (b) Landing. (c) ISRU.

controlled sampling operations. They also support subsurface drilling, which enables the collection of deeper and geologically diverse specimens [28]. The objective of these missions is to extract and transport high-value materials—such as precious metals and rare minerals—back to Earth for both scientific and commercial purposes.

On the other hand, as illustrated in Figure 2c, ISRU aims to process and utilize resources directly within the space base. This approach supports long-term deep space exploration and the development of extraterrestrial infrastructure by providing essential resources such as fuel, water, oxygen, and construction materials. ISRU is considered critical for reducing the cost and logistical complexity of interplanetary missions, as well as for enabling a sustainable human presence beyond Earth [29].

2.3 | Milestones in Small-Body Exploration

As mission objectives and capabilities have evolved, the modes of small-body exploration have expanded significantly—now encompassing flyby, orbiting, impact, landing, and sample-return operations. A timeline illustrating the major milestones in asteroid sampling missions is shown in Figure 3.

Launched in 1999, NASA's *Stardust* mission, which collected samples from comet 81P/Wild 2, marked the first successful return of cometary material to Earth [36, 37]. In 2003, Japan launched *Hayabusa*, the first near-Earth asteroid sample-

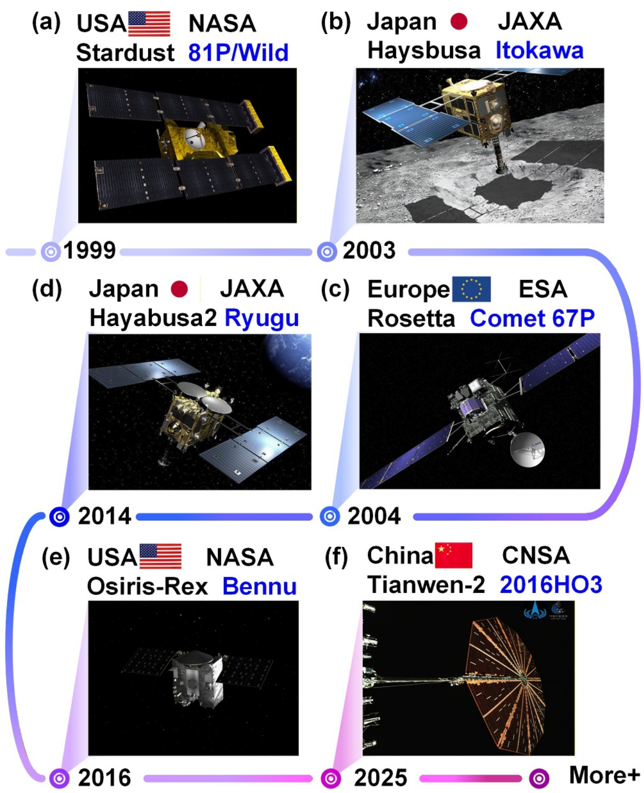

FIGURE 3 | Milestones in small-body sampling exploration missions. (a) Stardust [30]. (b) Hayabusa [31]. (c) Rosetta [32]. (d) Hayabusa2 [33]. (e) OSIRIS-REx [34]. (f) Tianwen-2 [35].

return mission [38], which successfully carried out a TAG sampling operation on asteroid 25,143 Itokawa [39]. In 2004, ESA launched *Rosetta* [40], the first spacecraft designed to rendezvous with and study a cometary small body. Its lander *Philae* achieved the first soft landing on comet 67P/Churyumov–Gerasimenko, performing in situ measurements [41–43]. In 2014, Japan launched *Hayabusa2* [44], which employed an improved TAG method to explore asteroid 162,173 Ryugu [45–47]. In 2016, NASA launched *OSIRIS-ReX*, its first asteroid sample-return mission, which orbited and collected samples from asteroid 101,955 Benn [48, 49]. In 2025, China's *Tianwen-2* mission is launched aboard a Long March 3B rocket. It aims to conduct multiple tasks, including co-orbiting, sampling, and returning from asteroid 2016 HO3, as well as a flyby investigation of main-belt comet 311P/PANSTARRS [50].

3 | Asteroid Sampling Robots

3.1 | Sampling Techniques

3.1.1 | Sampling Techniques in Current Missions

Sample acquisition from small bodies is a critical component of deep space exploration. Sampling techniques are generally classified into two categories: contact-based and noncontact-based. A comparative overview of these techniques is provided in Table 1.

Contact-based sampling methods are mainly divided into TAG and anchored sampling. TAG techniques rely on brief surface contact—often assisted by projectiles or gas jets—to acquire milligram- to gram-scale surface samples within a short time window. As shown in Figure 4a, Japan's *Hayabusa* mission pioneered this method by performing a one-second surface contact on asteroid Itokawa. A tantalum projectile was fired to eject surface particles, resulting in the recovery of over 1500 micron-scale grains [55]. Although the sampling mechanism malfunctioned and limited the total yield, the mission validated the feasibility of transient sampling under microgravity conditions. Building upon this, *Hayabusa2* employed an improved TAG system on asteroid Ryugu, successfully returning 5.4 g of material [56]. NASA's *OSIRIS-REx* mission further advanced TAG with its nitrogen gas–based TAG Sample Acquisition Mechanism (TAGSAM). Across three contact attempts within a 5-s window, the system collected approximately 121.6 g of regolith from asteroid Bennu [57]. The mission achieved centimeter-level navigation accuracy and precise contact dynamics control, while its multilayered collection head enabled efficient capture of samples ranging in size from microns to centimeters [58, 59]. Collectively, these achievements highlight TAG as a fast, low-risk method to sample acquisition; however, its intrinsic limitation lies in the restricted sample volume and surface-only collection capability. Future development is expected to focus on high-precision autonomous navigation and multi-site sampling, thereby enhancing the representativeness of collected materials.

Anchored sampling, by contrast, involves landing and establishing firm contact with the surface through anchoring devices, followed by collection via robotic arms or drilling systems. This approach enables larger sample volumes and access to subsurface layers, providing more geologically diverse and representative materials. However, its technical complexity and operational risks are considerably higher. The failure of ESA's *Philae* lander on comet 67P underscores these challenges [60, 61]. Despite employing a triple anchoring system—comprising harpoons, ice screws, and thrusters—the lander failed to secure itself due to inaccurate surface strength estimation and system malfunction, leading to incomplete sampling operations [62, 63]. This case revealed the urgent need for lightweight, adaptive, and redundant anchoring mechanisms to ensure stable operation in uncertain and heterogeneous environments [64].

As shown in Figure 4b, noncontact sampling methods rely on capturing ejected particles or inducing material release without physical landing, making them particularly suitable for volatile or hazardous terrains. NASA's *Stardust* mission exemplified this approach by using aerogel collectors to capture dust during a flyby of comet Wild 2, successfully returning samples containing organic compounds such as glycine [65]. Although this method eliminates the risks associated with surface contact, it remains constrained by low and stochastic sampling yields and limited sample representativeness. Current research is moving toward active stimulation methods, such as laser ablation and kinetic impacts. These approaches are often combined with advanced collection media to improve capture efficiency.

In summary, contact-based and noncontact-based sampling methods demonstrate exhibit complementary advantages. TAG

TABLE 1 | Advantages, limitations, and prospects of small-body sampling technologies.

Sampling mode	Technique	Core advantages	Main limitations	Future breakthroughs
Contact-based	TAG	Fast and low risk	Limited sample mass and surface-only	High-precision navigation and multi-site sampling
	Anchored sampling	Large sample size and subsurface material	Complex systems and high cost	Lightweight anchoring systems
Noncontact-based	Flyby collection	No landing risk	Low and random yield	Active ejection and advanced collection media

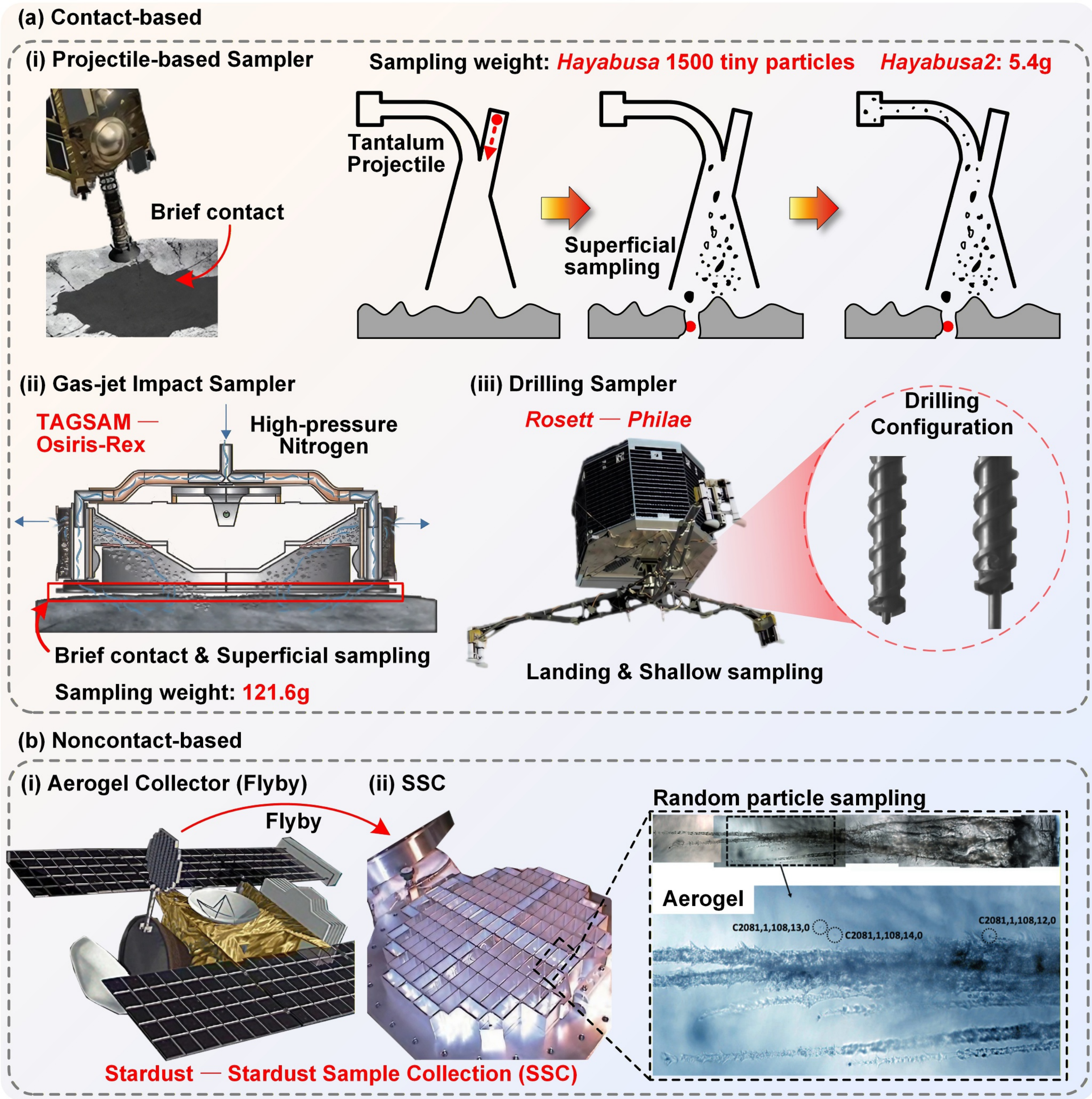

FIGURE 4 | Schematic of small-body sampling technologies. (a) Contact sampling methods. Two main variants of the TAG sampling method can be distinguished: (i) Projectile-based sampler [38] and (ii) gas-jet impact sampler [51]. (iii) The landing-based sampling method employing a drilling sampler [52]. (b) Noncontact sampling methods. (i) The Stardust spacecraft [53]. (ii) SSC. Reproduced with permission [54]. Copyright 2019, Wiley.

techniques emphasize safety and efficiency, anchored sampling enables comprehensive material acquisition, and noncontact methods provide risk-averse solutions for complex or volatile targets. However, none of these methods alone can fully satisfy the diverse requirements of small-body missions. The emerging trend points toward hybrid sampling architectures, integrating TAG, anchored, and noncontact strategies to achieve higher adaptability, robustness, and scientific yield in the uncertain environments of asteroids and comets.

3.1.2 | Other Potential Sampling Techniques

In addition to the widely adopted contact-based and noncontact sampling approaches, a range of emerging or potential sampling techniques have been proposed to address the challenges of small-body environments. These methods aim to expand the diversity of retrievable samples and enhance adaptability under uncertain conditions. As summarized in Table 2, the main categories include drilling-based methods, mechanical brushing or abrading systems, hovering-assisted techniques, and unconventional collection strategies such as net or harpoon capture.

Drilling remains the most direct method for accessing subsurface or consolidated layers [17, 75]. An integrated autonomous mechanism (IAM) has been proposed, combining two novel technologies: the Single Half and Percussive (SHaPe) system, which enables efficient coupling and de-coupling of drill halves from a bi directional screw, and an innovative multi-sample acquisition technique (MSAT). The latter allows multiple subsurface samples to be collected during a single drilling operation without retracting the bit between cycles, thereby significantly reducing operational time, drill wear, and power consumption while lowering the risk of mechanical failure or jamming [66]. Collectively, this design demonstrates the feasibility of modular, efficient, and reliable subsurface sampling for future small-body missions (Figure 5a(i)). Distinct from conventional single drill head designs, the Autonomous Asteroid Drilling System (AADS) adopts a modular architecture featuring segmented drill rods and casing that can be rapidly assembled and disassembled [76]. This modularity enables flexible bit selection, enhancing drilling efficiency and reliability, as illustrated in Figure 5a(ii). Another advancement is the Multi-Wireline Core Drilling Robot (MWDR), which integrates a drilling unit, a manipulator for tool handling, and a core collection system [77]. As shown in Figure 5a(iii), MWDR is designed for automated and efficient retrieval of subsurface cores, thereby addressing the challenge of limited operational windows in space environments.

Brush wheels and grinding systems have been investigated as complementary methods for sampling unconsolidated regolith. Figure 5b depicts that a symmetric dual-brush structure has been proposed, supported by a dynamic interaction model between brushes and particles to determine optimal operational parameters [68]. Extending this concept, a hybrid brush–grinder sampler has been designed to first grind the rock surface into finer fragments and then sweep the loosened material into the collection system [69]. Such designs offer structural simplicity and controllability while reducing reaction forces, though they remain limited to shallow regolith layers.

Hovering-assisted sampling approaches avoid direct surface contact by maintaining the spacecraft or sampling unit in a controlled position above the surface, while gas jets or other disturbance mechanisms mobilize particles for capture. For instance, China's *Tianwen-2* mission plans to implement a hybrid solution that combines hovering, TAG, and anchored sampling via robotic arms and gas-jet systems [80, 81]. Although still conceptual, hovering-assisted sampling provides a risk-averse and adaptable approach for volatile-rich or topographically hazardous small bodies.

Unconventional strategies, such as net entanglement [73] or harpoon penetration [82], have also been proposed. These methods offer the possibility of retrieving large, cohesive samples—including boulders or bulk regolith—in a single operation, thereby serving both scientific investigations and resource utilization objectives. A representative concept is NASA's Asteroid Redirect Mission (ARM) [83], which envisioned capturing a several-meter-scale boulder from a near-Earth asteroid using a deployable robotic arm in combination with anchoring and net-like containment. Although the mission was ultimately canceled, its design studies provided valuable insights into the feasibility and engineering requirements of large-scale capture operations. Nevertheless, the high dynamic

TABLE 2 | Comparative analysis of potential sampling techniques for small-body exploration.

Technique	Core advantages	Main limitations	Future prospects	Sampling weight
Drilling-based sampling	Subsurface access, pristine samples, and shielded from space weathering	High energy demand and microgravity reaction forces	Lightweight drills, adaptive force control, and in situ verification	10–100 g [66, 67]
Brushing/abrading mechanisms	Simple, controllable process, and low reaction forces	Limited to unconsolidated regolith and shallow depth	Backup method and hybrid multi-tool integration	10^{-3}–10^{1} g [68–70]
Hovering-assisted sampling	No contact risk and suitable for hazardous terrains	Requires high precision propulsion and energy	Micro-propulsion and closed-loop control	60–2000 g [71]
Net/harpoon-based capture	Large cohesive samples and bulk collection	Violent dynamics, structural risk, and no space demo yet	Ground testing and resource-oriented missions	10^{5}–10^{7} g [72–74]

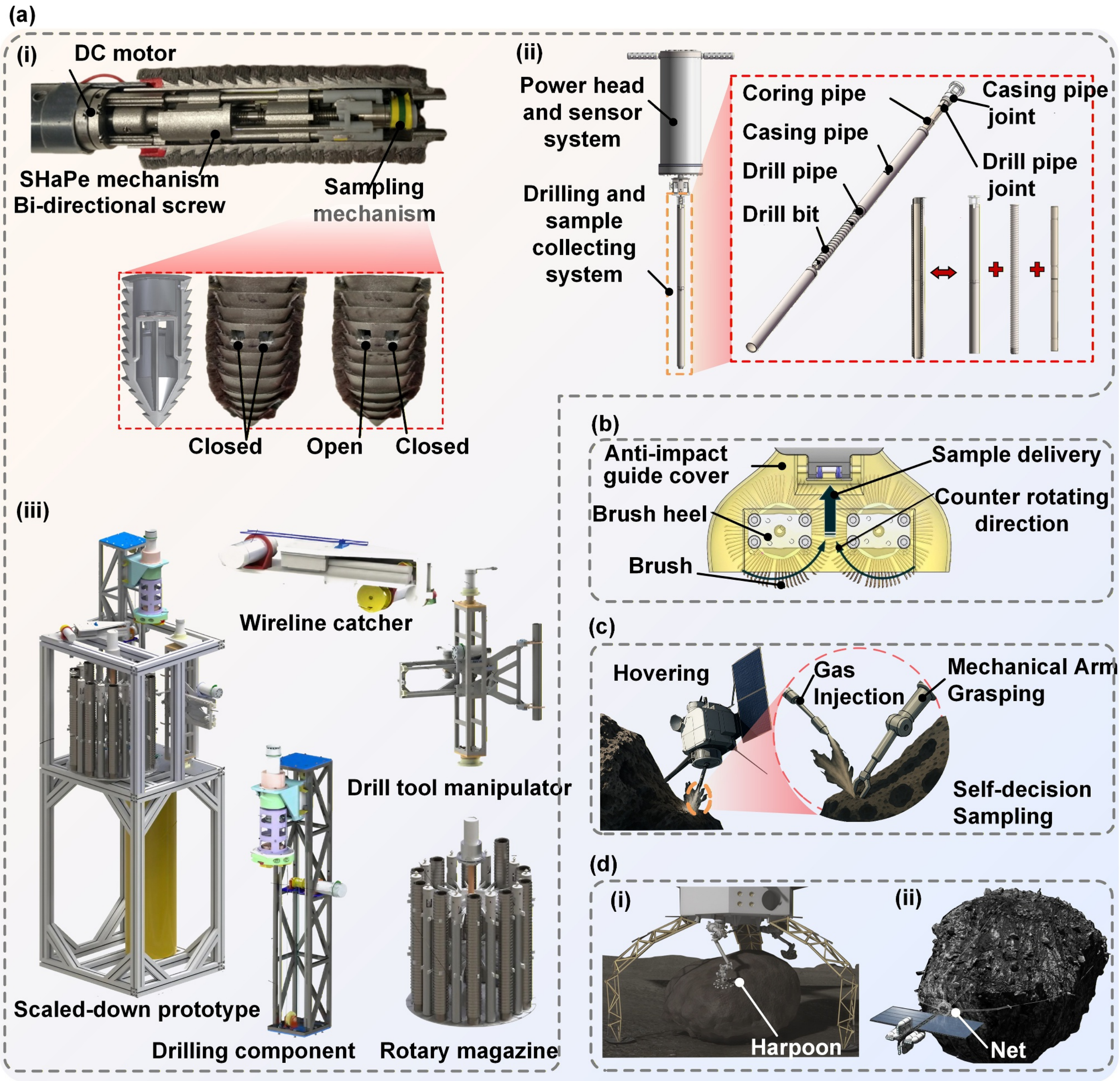

FIGURE 5 | Emerging contact-based sampling mechanisms. (a) Drilling-based sampling. (i) MSAM. Reproduced with permission [66]. Copyright 2022, Elsevier. (ii) AADS. Reproduced with permission [76]. Copyright 2023, Elsevier. (iii) MWDR. Reproduced with permission [77]. Copyright 2025, Elsevier. (b) Brushing/abrading mechanisms. Reproduced with permission [68]. Copyright 2022, Elsevier. (c) Hovering-assisted sampling. (d) Net/harpoon-based capture. (i) Harpoon penetration [78]. (ii) Net entanglement [72, 79].

forces and structural uncertainties inherent to such techniques still pose considerable risks, and no successful in situ space demonstration has yet been achieved.

Potential sampling techniques extend beyond the widely used TAG and anchored strategies, incorporating drilling innovations, mechanical brushing and abrading systems, hovering-assisted methods, and unconventional capture devices. While these approaches remain at lower technology readiness levels, they offer promising solutions to address the challenges of microgravity, surface heterogeneity, and mission safety. Future research should prioritize lightweight system integration, energy efficiency, and adaptive control mechanisms, thereby advancing these emerging concepts toward practical deployment in upcoming small-body missions.

3.1.3 | Comparative Evaluation of Sampling Concepts for System Design

To facilitate system-level comparisons, Table 3 summarizes representative sampling approaches using a set of mission-relevant metrics, including depth capability, yield potential, sampling risk, surface dependence, contamination, mass–power burden, autonomy burden, and maturity. In Table 3, a simple

TABLE 3 | Mission-driven comparative matrix of sampling techniques.

Metric	TAG	Arm/scoop/grab	Drilling/coring	Flyby	Hover-assisted	Net/harpoon-based
Depth capability	L	M	H	L	L–M	M
Yield potential	M	M	M–H	L–M	M	H
Sampling risk	M	M–H	H	L	M	H
Surface dependence	M	H	H	L	L–M	M
Contamination	M	M–H	H	M	M	M
Mass–power burden	L–M	M–H	H	M	H	H
Autonomy burden	H	M–H	H	M	H	H
Maturity	H	M	L–M	H	L	L

three-level scale—H/M/L (high/medium/low)—is adopted to provide a relative assessment for concept screening and trade-off studies. Importantly, these ratings should be interpreted as decision-oriented guidance rather than standardized benchmarks, because the reported performance of a given method can vary substantially with target properties and operational constraints.

TAG emphasizes brief contact and rapid retreat, reducing surface dwell time and operational exposure. However, it requires tight GNC and careful management of contact impulse, and its yield can be highly sensitive to local regolith conditions. Arm/scoop/grab sampling supports fixed-point, repeatable operations and more controlled manipulation and transfer pathways, but it shifts the dominant risks to reaction-load coupling (tool forces/torques), anchoring and attitude stabilization reliability, and uncertainty in surface bearing capacity. Drilling/coring provides the strongest pathway to subsurface and potentially pristine material, yet it imposes the highest requirements on force–torque accommodation, anchoring synergy, and power budgets. Flyby sampling minimizes the risks associated with direct surface interaction and reduces dependence on surface bearing strength, but it typically suffers from stochastic yield and stringent constraints on relative trajectory control and capture efficiency. Hover-assisted concepts offer an intermediate route for hazardous terrains by combining controlled proximity with excitation and capture, at the cost of higher propulsion demand and challenges related to dust-plume visibility and contamination control. Finally, net/harpoon-based capture concepts can target large fragments with high yield potential, but they introduce system-level challenges in impact dynamics as well as safe containment, release, and retreat.

Sampling concepts that minimize contact duration and operational exposure tend to align with risk-averse profiles, whereas concepts targeting subsurface access and higher yield generally require stronger tolerance to reaction loads and tighter integration with mobility and anchoring. Under large uncertainty in surface properties, the preferred options are those with broader operating envelopes and more controllable contact dynamics. The feasibility of each option should then be judged against the available mass and power budget, the required level of onboard autonomy and guidance performance, and the stability margins provided by the chosen mobility and anchoring architecture. In this way, the matrix provides a consistent basis for comparing sampling concepts and for translating mechanism-level differences into system-level design trade-offs.

3.2 | Mobility Strategies

3.2.1 | Current Mobility Strategies

Small bodies exhibit highly irregular shapes and chaotic gravitational fields [84]. Their extremely low gravity offers insufficient traction for conventional wheeled rovers, while the terrain is often rugged and lacks extensive flat regions. Additionally, escape velocities are minimal. These factors significantly increase the risk of unintended rebound or loss of attitude control during robotic operations. Consequently, traditional locomotion and anchoring technologies are largely unsuitable for such environments. This fundamental distinction differentiates small-body exploration from planetary surface missions. Current mobility strategies for sampling robots on small bodies can be categorized into four main types: hopping locomotion, anchoring-assisted mobility, leg-based locomotion, and short-duration contact maneuvers coupled with sampling (e.g., TAG), as summarized in Table 4 and illustrated in Figure 6.

Hopping locomotion exploits inertial or propulsive actuation (rotors, swing arms, springs, or small thrusters) to perform controlled short-range translational moves in microgravity. Although hopping avoids the need for continuous surface traction, it imposes strict requirements on descent control and touchdown stability [87]. A landmark demonstration of this approach was achieved by Japan's *Hayabusa2* mission, which successfully deployed the MINERVA-II-1 rover on the surface of asteroid Ryugu. Weighing only 1.1 kg, the rover employed a unique hopping mechanism based on rotating internal mass blocks. Through the centrifugal force generated by an internal eccentric motor—capable of spinning at up to 6000 rpm—it achieved multiple autonomous hops in Ryugu's ultralow gravity environment (~10^{-4} g). The system attained a maximum hopping height of 15 m and a total horizontal displacement of over 30 m. The mission validated the feasibility of long-distance hopping mobility under microgravity, with autonomous navigation accuracy controlled within $\pm$ 10 cm.

In parallel, the Mobile Asteroid Surface Scout (MASCOT) lander, also deployed by *Hayabusa2*, provided another successful demonstration of hopping mobility. With a mass of 10 kg, MASCOT was equipped with an internal swing arm mechanism that could be actuated to generate inertial forces, enabling the lander to reorient itself and perform discrete hops across the surface of Ryugu. This design allowed MASCOT not only to relocate for multi-point measurements but also to

TABLE 4 | Comparative analysis of mobility modes for small-body sampling robots.

Mobility mode	Applicable gravity (g)	Speed (cm/s)	Obstacle crossing	Technology readiness level (TRL)
Hopping	$< 10^{-4}$	2–10	High	TRL7 [44, 46]
TAG	Any	—	None	TRL9 [38, 39, 45, 47]
Anchoring-assisted	$< 10^{-3}$	0.1–1	Moderate	TRL5 [41, 43]
Hybrid	Any	1–8	High	TRL3 [85, 86]

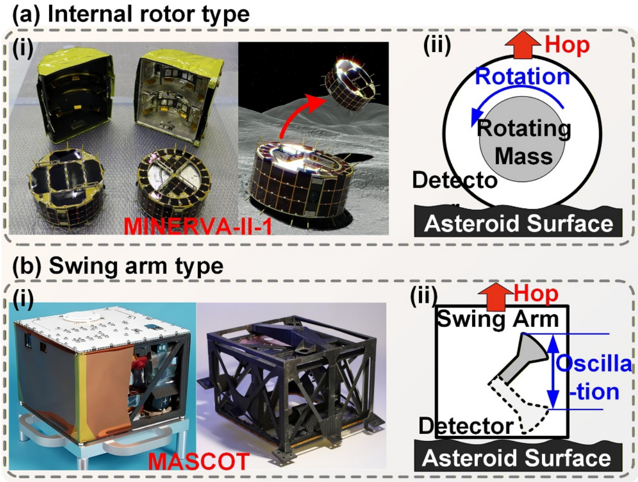

FIGURE 6 | Mobility modes of small-body sampling robots. (a) Internal rotor type. (i) MINERVA-II-1. (ii) The working principle of rotating mass. (b) Swing arm type. (i) MASCOT. (ii) The working principle of the swing arm.

autonomously adjust its orientation to ensure proper alignment of scientific instruments. Although limited by a 17-h battery lifetime, MASCOT successfully conducted four instrument-based experiments and completed multiple relocations, highlighting the effectiveness of swing arm–based hopping under extreme microgravity conditions.

Unlike continuous locomotion modes, TAG represents a hybrid mobility–sampling operation, where the probe executes a controlled descent, brief surface contact for sample acquisition and immediate ascent. Although not a sustained locomotion mode, TAG is included here because its execution requires precise mobility control during descent and ascent, tightly coupling movement with sampling functionality. TAG involves momentary contact with the surface for sampling, offering a simple yet limited collection approach. NASA's *OSIRIS-REx* demonstrated this method on Bennu, descending from orbit to surface contact in just 5 s and collecting 121.6 g of material via nitrogen gas ejection—validating the feasibility of fast contact mobility.

Anchoring-assisted mobility uses mechanical devices to fix the probe for stable sampling or long-duration observation, especially on steep or irregular terrain. A representative case is ESA's *Philae* lander, which attempted to anchor on comet 67P/Churyumov-Gerasimenko using a triple-fixation system (harpoons, ice screws, and cold gas thrusters). However, the mission failed due to surface hardness misestimation and system malfunction, leading to uncontrolled rebound [88].

Wheeled mobility offers strong controllability via specially designed wheels but is prone to getting stuck in loose regolith. It remains largely experimental and is more promising for larger bodies such as Martian moons [89, 90].

Hybrid mobility combines multiple locomotion principles into a single platform to improve adaptability across diverse terrain conditions. For example, recent designs [91] explored combinations of wheeled motion and bioinspired crawling modules, which can switch between rolling, creeping, or climbing depending on the surface environment. Although these systems remain at low technology readiness levels (TRL 2–3), they represent a promising direction toward multifunctional robots capable of balancing efficiency, stability, and adaptability [85, 86]. Hybrid approaches are expected to benefit future missions where the surface environment is highly uncertain and single-mode locomotion may not provide sufficient robustness.

At present, hopping and TAG techniques are the most mature mobility solutions. Wheeled locomotion shows promise on larger low-gravity targets, whereas anchoring systems still require critical technological breakthroughs. Future trends are expected to favor intelligent hybrid systems that combine AI navigation, novel actuators, and lightweight design. Such systems will be tailored to specific celestial targets, mission requirements, and engineering constraints—paving the way toward smart, adaptive mobility.

3.2.2 | Emerging and Potential Mobility Strategies

Although hopping, TAG, and anchored mobility have been validated in space missions, a number of potential mobility technologies are under active exploration for future small-body missions. These emerging approaches aim to overcome the intrinsic challenges posed by ultralow gravity, rugged topography, and unpredictable surface properties. The principal categories include hopping locomotion, climbing or anchoring systems, and creeping or wriggling mechanisms, each of which provides unique advantages and faces specific technical barriers. A comparative overview is presented in Table 5.

Hopping locomotion exploits the dynamics of microgravity for semi-controlled relocation. A landmark example is the Hedgehog robot, jointly developed by NASA JPL, Stanford University, and MIT (Figure 7a(i)). The system employs internal reaction wheels to generate torque, enabling controlled tumbling and hopping without external appendages. As shown in Figure 7a(ii), Beihang University's tetrahedral robot relies on shifting its internal mass to roll or flip across rugged terrain [93]. Kinematic

TABLE 5 | Comparative analysis of potential mobility technologies for small-body robots.

Technology	Core advantages	Main limitations	Future prospects
Hopping locomotion	Exploits natural dynamics, simple mechanisms, and energy-efficient	Poor trajectory control and risk of escape from the surface	Controlled hopping with adaptive navigation and integration with sensors for trajectory correction
Climbing or anchoring mobility	Strong stability on steep slopes and enables long-duration local operation	High anchoring uncertainty and risk of rebound if anchoring fails	Adaptive multimode anchoring and combined climbing–sampling platforms
Creeping/ wriggling locomotion	High adaptability to irregular terrain and stable surface contact	Extremely slow speed and high mechanical complexity	Biomimetic designs and modular creeping robots for microgravity environments

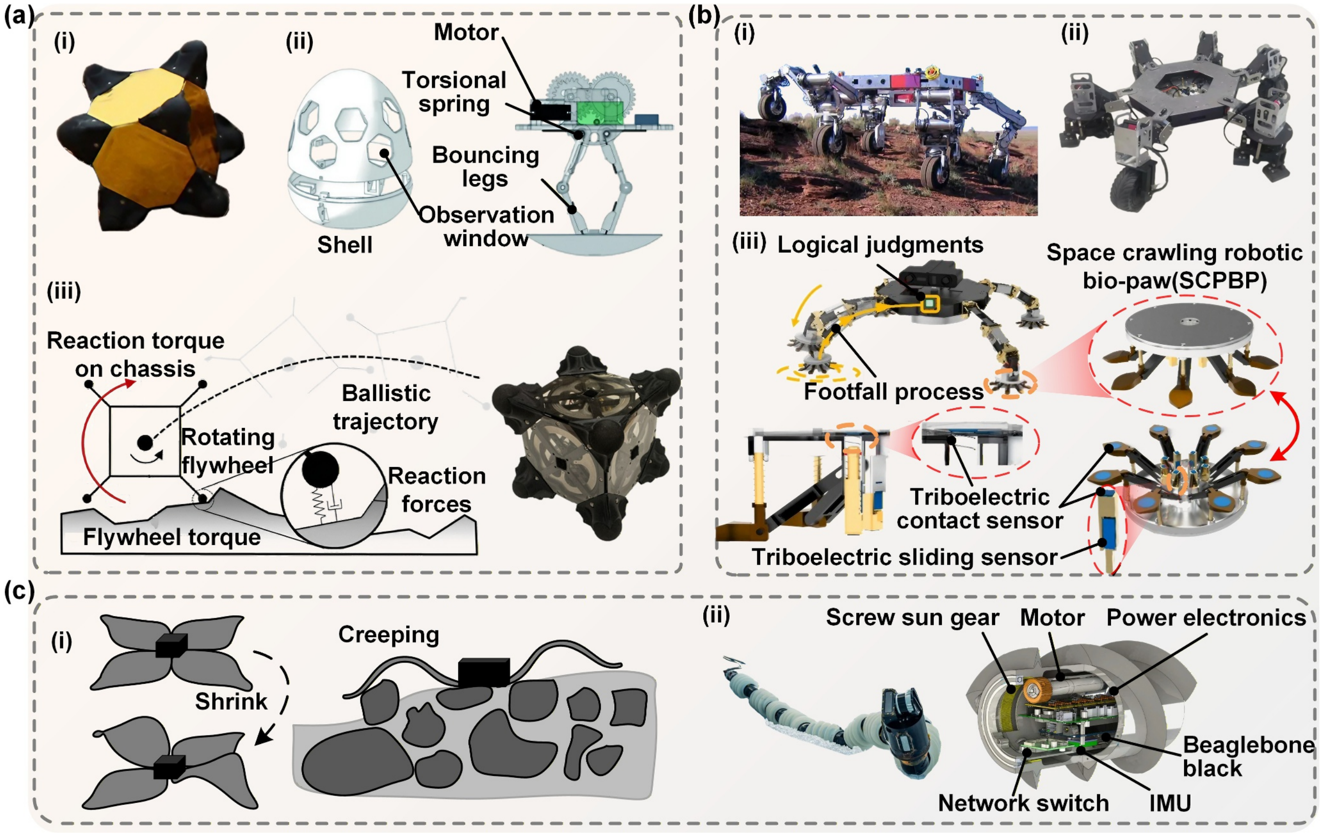

FIGURE 7 | Advanced and potential mobility mechanisms for small-body sampling robots. (a) Hopping locomotion. (i) Hedgehog [92]. (ii) Tetrahedral robot [93]. (iii) Hopper [94]. (b) Climbing/anchoring mobility. (i) ATHLETE [95]. (ii) Three-wheel three-legged type. (iii) SCRBP. Reproduced with permission [96]. Copyright 2023, Elsevier. (c) Creeping/Wriggling locomotion. (i) AoES. (ii) ARCSnake [97].

modeling, dynamic simulations, and physical prototyping have verified its feasibility. In addition, a spring-actuated hopper with a compact egg-shaped shell and parallel legs has been developed by Nanjing University of Aeronautics and Astronautics (Figure 7a(iii)), optimized for environments where wheeled mobility is infeasible [94].

Climbing robots, in particular, are designed to achieve stable mobility by anchoring themselves onto regolith or rocky surfaces. As shown in Figure 7b(i), NASA JPL proposed an All-Terrain Hex-Limbed, Extra-Terrestrial Explorer (ATHLET). This vehicle concept is capable of efficient rolling mobility on moderate terrain and walking mobility on extreme terrain. Each limb has a quick-disconnect tool adapter so that it can perform general-purpose handling, assembly, maintenance, and servicing tasks using any or all of the limbs [98]. Inspired by the moving mechanisms of arthropod insects, woodpeckers, and origami techniques, Figure 7b(ii) proposed an integrated moving–anchoring–sampling bionic robot for asteroid complex environments (MASbot). Relying on only three anchoring structures, MASbot can generate an anchoring force equivalent to 1.53 times its own weight and is capable of completing target acquisition tasks. Furthermore, bioinspired solutions such as the Soft Compliant Robotic Bio-Paw (SCRBP; Figure 7b(iii)) replicate feline paws with eight compliant toe groups, capable of absorbing impact and conforming to irregular terrain [96]. Integrated into crawling platforms, the SCRBP generates contact-dependent voltage signals that dynamically adjust gaits, improving environmental adaptability and energy efficiency. Another representative design is the microgravity rover developed by the University of Tokyo (Figure 7b(ii)), which employs spike-tipped legs to penetrate loose regolith and provide stable walking support under weak gravitational conditions [99].

Creeping and snake-like mobility emphasize continuous surface contact, providing stability and adaptability in ultralow gravity. The Area-of-Effect Soft (AoES) robot [100] employs four compliant petal-shaped limbs driven by dielectric actuators, enabling creeping, climbing, and escape hopping maneuvers (Figure 7c(i)). Its electrostatic adhesion capability allows attachment to rubble pile surfaces, reducing rebound risks during sampling. The Archimedean spiral snake (ARCSnake) [101, 102] adopts screw-driven spiral modules connected via universal joints (Figure 7c(ii)). It can burrow into soft regolith by rotating its spiral shells, switch to wheel-like serpentine motion on hard terrain, and navigate narrow tunnels using head-guided locomotion. This modular design offers strong versatility and reliability. Building on such concepts, NASA's Exobiology Extant Life Surveyor (EELS) aims to traverse fissures in Enceladus's icy crust to explore subsurface oceans, highlighting the broader applicability of snake-inspired designs [103, 104].

Recent prototypes—from the Hedgehog and tetrahedral robots to bioinspired devices such as SCRBP—demonstrate the growing emphasis on intelligent, adaptive, and biomimetic locomotion for small-body exploration. Although most remain at low technology readiness levels, these technologies significantly expand the mobility design space and are expected to play an increasingly vital role in future long-duration and high-risk planetary missions.

3.2.3 | Comparative Evaluation of Mobility Concepts for System Design

Table 6 summarizes representative mobility strategies against mission-relevant metrics, including trajectory controllability and landing predictability, terrain adaptability and obstacle negotiation, contact stability for sustained operations, escape safety under microgravity disturbances, energy efficiency, sensing and navigation burden, system complexity, and maturity. In Table 6, metrics marked with an asterisk are cost- or risk-oriented, and for these metrics, H indicates a higher burden or higher risk rather than a better performance. These ratings should not be interpreted as standardized benchmarking because mobility on small bodies is dominated by microgravity contact dynamics and operational constraints. The very small gravitational acceleration limits normal force and traction, reduces passive self-stabilization, and makes even modest contact impulses comparable to the local escape velocity budget. As a result, small variations in contact conditions, regolith response, and attitude state can lead to disproportionately large changes in post-contact motion, rebound, and attitude disturbance.

Hopping leverages ballistic relocation to bypass local obstacles and compensate for weak traction. However, it is inherently sensitive to impulse uncertainty and restitution effects; consequently, escape safety and landing predictability can deteriorate when surface stiffness and particle-scale mechanics are poorly known. TAG represents a tightly constrained mobility mode aligned with sampling objectives, where brief contact and rapid retreat reduce surface exposure, yet the same microgravity conditions that enable fast retreat also amplify sensitivity to contact impulse, attitude disturbance, and dust lofting, placing stringent demands on control and predictability. Anchor-assisted motion emphasizes stable progression by establishing deliberate contact constraints, which is advantageous when operations must tolerate reaction loads, but it transfers feasibility to reliable engagement and release on uncertain surfaces and increases system complexity.

Wheeled mobility can provide efficient continuous traversal when normal force and traction are sufficient, but in microgravity, it is more prone to slip, reduced steering authority, and local sinkage events that can trigger attitude excursions. Legged mobility improves adaptability and contact stability through multipoint support and compliance, yet its benefits depend on maintaining reliable ground reaction forces, which are weakened by low gravity and can increase sensitivity to contact timing and surface heterogeneity. Creeping maintains continuous contact and conservative motion, which can suppress rebound-related hazards and improve stability margins, but it often sacrifices traversal efficiency and can increase integration demands for sustained contact management. Hybrid mobility seeks robustness across heterogeneous terrains by switching

TABLE 6 | Mission-driven comparative matrix of mobility strategies.

Metric	Hopping	TAG	Anchoring-assisted	Wheeled	Legged	Creeping	Hybrid
Control/predictability	M	H	M	H	M	M	M
Terrain adaptability	H	L–M	M–H	M	H	H	H
Contact stability	L	M	H	M	H	H	M–H
Escape safety	L–M	M	M–H	M	M–H	H	M
Energy efficiency	M	M	L–M	H	M	L–M	M
Sensing/navigation and closed-loop control burden	M–H	H	M	M	M–H	M	H
Mechanical/control complexity	M	M	H	M	H	H	H
Maturity	H	H	M	L–M	L–M	L	L

among modes according to local conditions and trading expanded capability for higher navigation, estimation burden, and greater system complexity to ensure safe transitions without accumulating momentum that jeopardizes escape safety.

Missions prioritizing rapid multi-site access must manage the momentum budget conservatively, because contact impulses and attitude disturbances can accumulate into escape or uncontrolled rebound events. Missions requiring sustained interaction, precise placement, or high reaction-load tolerance benefit from mobility concepts that maintain stable contact and predictable force closure, even if traversal speed is reduced. Under large uncertainty in regolith mechanics and terrain morphology, the preferred options are those with broader operating envelopes and more predictable contact outcomes rather than those relying on traction assumptions that may not hold. The feasibility of each option should then be judged against the available mass and power budget, the achievable navigation accuracy, and the stability margins provided by the anchoring architecture, because in microgravity, mobility, sampling, and anchoring are coupled through contact dynamics and shared momentum management.

3.3 | Anchoring Methods

3.3.1 | Taxonomy and Working Principles of Anchoring Methods

Unlike sampling and mobility technologies, anchoring mechanisms for small-body robots are yet to achieve a fully successful in-space demonstration. The only attempted application—the harpoon anchors on ESA's *Philae* lander—failed due to unexpected surface properties, whereas other concepts remain at laboratory or prototype stages. Nevertheless, anchoring remains a critical enabling technology for future missions. Landing and in situ exploration can greatly enhance sampling efficiency and scientific return [29]. However, due to the extremely weak gravity—typically ranging from 10^{-3} to 10^{-5} g—and escape velocities as low as 20 cm/s [105, 106], landers are highly susceptible to detachment. This risk can be triggered by various factors, including reaction forces during sampling, thruster backblast, solar radiation pressure, and magnetic perturbations. Reliable anchoring systems are therefore indispensable to achieve stable and sustained operations on small celestial bodies. Current anchoring approaches can be broadly categorized into mechanical penetration, grasping-based anchoring, adhesive systems, and hybrid systems, as summarized in Table 7.

Mechanical penetration represents the earliest and most widely adopted anchoring approach. A well-known case is ESA's *Philae* lander, which attempted to secure itself on comet 67P using dual harpoons designed for 0.1 MPa compressive strength. The actual surface strength, however, exceeded 2 MPa due to an organic crust, causing anchoring failure. This revealed key challenges including inaccurate surface property prediction, insufficient system redundancy, and poor modeling of lander–surface interactions in ~10^{-4} g conditions. Inspired by this, Zhao et al. [112] developed a Philae-inspired prototype capable of generating 30–178 N anchoring force under varied soil conditions (Figure 8a(ii)). More recently, a novel sawing-based anchoring system has been proposed, consisting of three robotic arms, three cutting discs, and an integrated control unit, as shown in Figure 8a(iii). In this design, the discs mounted at the arm tips were cut into the asteroid's rocky surface, after which the self-locking mechanism of the arms provides stable fixation for the lander [113]. Other designs include Steltzner's gas-driven spike system and Honeybee Robotics' segmented rotary-drilling anchor, optimized for rubble pile asteroids [72, 117].

Grasping systems use mechanical appendages to seize surface protrusions or embed claws into cracks. NASA JPL developed micro-spine anchors, with arrays of independently actuated steel barbs locking into pits and asperities [114]. Parness et al. introduced the Nautilus gripper [115], whereas Ding Xilun's group developed the beetle-inspired climbing robot RockClimbo [118], equipped with multiple clawed feet and a probabilistic adhesion model (Figure 8b). These solutions provide strong stability on rough terrain, but their performance depends heavily on surface morphology.

Adhesive-based anchoring (e.g., gecko-inspired dry adhesives and electroadhesion) provides noninvasive and reversible attachment, making it attractive for fragile surfaces where penetration is risky. However, its primary bottleneck for small-body operations is dust-induced degradation: fine regolith and debris can accumulate within microstructured arrays and at the interface, reducing the real contact area and degrading adhesion. For engineered dry adhesives that lack the hierarchical nanoscale features of biological geckos, contamination can

TABLE 7 | Comparative analysis of anchoring methods for small-body robots.

Anchoring type	Suitable surface	Pros and cons	Representative mission	Execution information	Anchoring force
Mechanical penetration	Loose, weathered surfaces	Strong anchoring force and dependent on soil properties	*Philae*	Successful (2014) and anchoring failed	10^1–10^2 N [107]
Grasping-based	Exposed bedrock	Reusable and terrain-dependent	*OSIRIS-REx*	Ongoing (launched in 2016)	10^2–10^3 N [108]
Adhesive-based	Flat, dense surfaces	Noninvasive, energy intensive, and sensitive to dust	Laboratory stage	Not yet executed	10^0–10^2 N
Hybrid systems	Heterogeneous terrain	Broad adaptability and high complexity	*MMX*	Scheduled for 2026 launch	10^1–10^3 N [109–111]

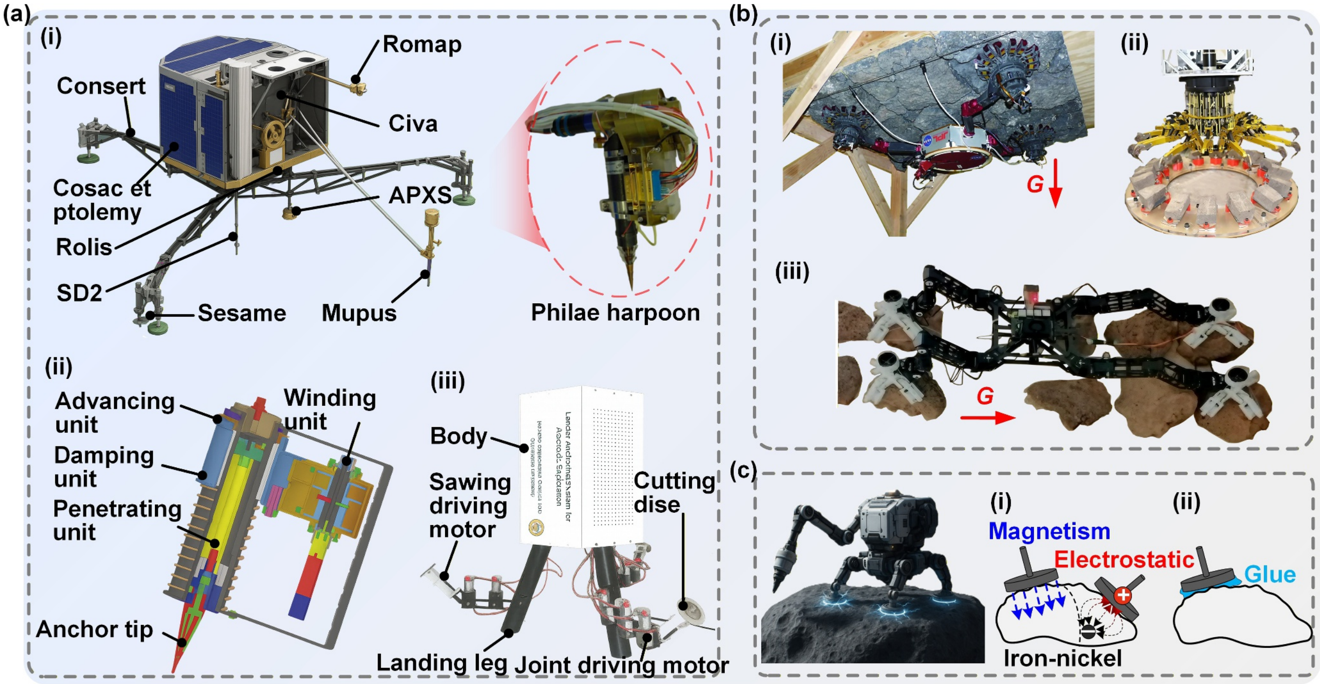

FIGURE 8 | Representative anchoring mechanisms for small-body sampling robots. (a) Mechanical penetration. (i) Philae lander and its harpoon. Reproduced with permission [43] Copyright 2009, Elsevier. Reproduced with permission [63]. Copyright 2016, Elsevier. (ii) Philae-inspired prototype [112]. (iii) A lander anchoring system based on a sawing method for asteroid exploration. Reproduced with permission [113]. Copyright 2018, Elsevier. (b) Grasping-based anchoring. (i) Gravity-independent rock-climbing robot. Reproduced with permission [114]. Copyright 2013, Wiley. (ii) Nautilus gripper. Reproduced with permission [115]. Copyright 2020, Wiley. (iii) A gripper inspired by beetle claws. Reproduced with permission [116]. Copyright 2023, Elsevier. (c) Adhesive-based anchoring. (i) Field-based anchoring. (ii) Bonding anchoring.

nearly eliminate adhesion [119]. Consequently, cleanability and dust tolerance have become an explicit design objective.

Quantitatively, electroadhesion offers controllability but often delivers only kPa-level attachment on practical surfaces. For example, an interdigital Mylar electrostatic adhesive reports shear stresses of ~4 kPa on smooth glass and ~2 kPa on painted drywall [120]. Such systems typically require kilovolt-level driving potentials (commonly 1–6 kV, with reported values up to 20 kV) [121] and nonnegligible energy input, which constrains stable anchoring on dusty, heterogeneous regolith. To improve robustness across surface variability, hybrid electrostatic dry adhesive (EDA) concepts have been demonstrated to substantially boost performance, reaching ~49 kPa on smooth glass and ~33 kPa on a rough surface (~21 μm RMS). In addition, self-cleaning microarrays have been reported to enhance adhesion by ~1.5× [122]. Collectively, these advances support a co-design pathway that couples microtexture, material properties, and electrostatic assistance to achieve dust-tolerant attachment.

New systems aim to combine adaptability with autonomy. Gecko foot–like fibrillar structures can achieve up to 4.2 N/cm^2 adhesion while conforming to surface roughness. JAXA's *MMX* mission (launch planned for 2026) introduces a dual-mode intelligent anchor: It switches between electromagnetic adhesion (when Fe content > 30%) and mechanical claws, with adaptation completed within 0.5 s and resistance to 0.2 m/s^2 disturbances [123, 124]. Looking ahead, fourth-generation anchors will integrate real-time surface recognition, AI-based decision-making, and multimodal actuation, combining mechanical, magnetic, and adhesive strategies.

Anchoring technologies can be divided into four evolutionary stages, as shown in Figure 9.

The first generation of mechanical anchoring technologies (1960s–1990s) includes systems such as harpoons, screws, and spikes, which provide strong fixation through physical penetration. These technologies were demonstrated in the Apollo 11 mission in 1969, where simple mechanical penetration was used to interact with and characterize the regolith. During the 1970s–1990s, other space missions, including those by the Soviet Union, adopted similar mechanical anchoring systems for lunar exploration. Although these systems are mature and effective on simple, homogeneous surfaces, they struggle with heterogeneous terrains and complex surface types.

The second generation of adhesive-based anchoring technologies (1990s–present) introduced noninvasive methods, such as electrostatic pads and gecko-inspired adhesives, which minimize surface intrusion. These systems were initially validated in laboratory environments by agencies like NASA and ESA in the 1990s, and prototype tests continued into the 2000s. Although these systems offer noninvasive attachment and are suitable for delicate surfaces, their effectiveness remains limited by environmental factors such as dust contamination and temperature fluctuations, which can undermine adhesion reliability.

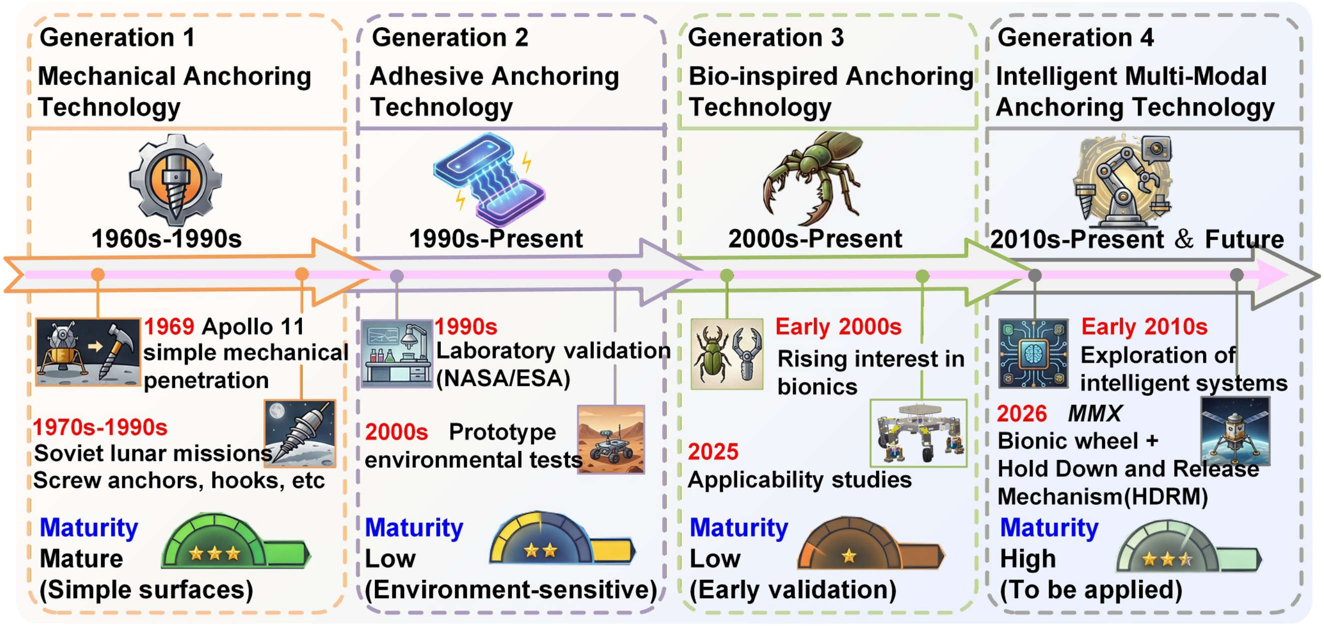

FIGURE 9 | Anchoring technology evolution timeline.

The third generation of bioinspired anchoring technologies (2000s–present) draws inspiration from nature, utilizing designs like micro-spine arrays and insect claw analogs to create high-strength, adaptable adhesion mechanisms. Interest in bio-inspired design grew significantly in the early 2000s, with agencies like NASA exploring how nature's solutions could be replicated to improve anchoring systems. However, these technologies are still in the early validation stages and are primarily confined to laboratory settings and early applicability studies, such as the ongoing research into micro-spines for enhanced gripping and anchoring.

The fourth generation of intelligent multimodal anchoring technologies (2010s–present) represents a frontier in small-body anchoring research. These systems combine mechanical, adhesive, and bioinspired methods with real-time surface sensing, autonomous decision-making, and adaptive switching between modes. The JAXA *MMX* mission, scheduled for 2026, is among the early missions expected to incorporate such concepts, featuring a bionic wheel and a Hold-Down and Release Mechanism (HDRM). These advancements aim to provide more robust, self-adaptive anchoring solutions for complex environments, marking a significant leap toward multifunctional, autonomous systems capable of handling unpredictable terrains on small celestial bodies.

3.3.2 | Comparative Evaluation of Anchoring Concepts for System Design

Table 8 summarizes representative anchoring concepts against mission-relevant metrics, including holding potential and stiffness, substrate dependence under uncertainty, dust tolerance, reusability and release control, power demand, deployment and failure risk, system complexity, sensing and autonomy burden, and maturity. These ratings are not intended as standardized benchmarking because anchoring performance on small bodies is strongly shaped by microgravity contact mechanics and uncertain surface conditions. Limited gravitational acceleration reduces normal force and passive stability, while highly variable regolith strength, roughness, and dust contamination can cause large variations in engagement quality and in the achievable holding capacity.

Mechanical penetration anchors can provide high holding capacity and stiffness when the substrate permits penetration, but they rely heavily on uncertain mechanical properties such as strength and penetrability, and a failed engagement may be difficult to recover from during a mission. Grasping-based anchors exploit geometric interlocking and multipoint contact, offering good reusability and controllable release when suitable features exist, yet their effectiveness depends on local morphology and their performance can degrade when dust reduces friction and contact reliability. Adhesive-based anchoring enables noninvasive and reversible attachment and can simplify repeated engagement, but it is typically sensitive to dust contamination and surface roughness, and its practical holding pressure can be limited or time-varying depending on the implementation and power constraints. Hybrid systems aim to reduce single-point failure by combining complementary mechanisms and switching modes according to local conditions and operational phases. This expands the viable operating envelope under uncertainty, but it increases integration complexity and often requires higher sensing and autonomy capability to support reliable mode selection and safe transitions.

Missions that require sustained contact stability or must withstand large reaction loads during sampling benefit from anchoring solutions with higher holding stiffness and predictable load paths, whereas missions emphasizing frequent repositioning and repeated operations benefit from reliable release control and high reusability. Under large uncertainty in surface

TABLE 8 | Mission-driven comparative matrix of anchoring methods.

Metric	Mechanical penetration	Grasping-based	Adhesive-based	Hybrid systems
Holding potential/stiffness	H	M–H	L–M	H
Substrate dependence	H	H	M–H	L–M
Dust tolerance	M	M	L–M	M–H
Reusability/release control	M	H	H	H
Power demand	M	L–M	M–H	M–H
Deployment/failure risk	H	M	M–H	M
System complexity	M	M	M	H
Sensing/autonomy burden	M	M	M	H

properties and dust conditions, the preferred solutions are those that remain functional across a broad range of substrates, avoiding reliance on a single surface assumption. The feasibility of each option should then be judged against the available mass and power budget, the allowable operational risk, and the sensing and autonomy capability required to ensure robust engagement and release. In this way, the comparative matrix provides a consistent basis for translating anchoring mechanism choices into system-level design trade-offs.

4 | Key Challenges and Bottlenecks

The core difficulty of small-body surface operations does not lie in any single technology in isolation, but rather in the dynamic coupling among sampling, mobility, and anchoring. Although traditional reviews often examine these modules separately, under conditions of microgravity, irregular topography, and uncertain surface properties, it is their interactions that primarily determine system stability, operational efficiency, and scientific yield. Table 9 and Figure 10 summarize the conflict–benefit mechanisms, representative strategies, and mission cases across the three pairwise interfaces.

4.1 | Sampling–Mobility Coupling

A critical aspect of the sampling–mobility interaction is the control of transient contact within escape velocity constraints. In TAG and hover-assisted scenarios, the dynamics of precise descent and retreat are tightly coupled with contact events [125]. Actions such as gas-jet firings, projectile deployment, and end-effector impact can impart impulses exceeding local escape velocity, leading to rebound, loss of attitude control, and degraded post-contact stability [48]. Additionally, dust plumes generated during these operations further impair perception and delay safe retreat. Conversely, controlled short-duration contact with rapid withdrawal reduces risk, whereas hopping or short relocations enhance the spatial representativeness of collected samples [126]. Mitigation strategies include compliant and force-limited end-effectors, plume-aware closed-loop descent systems, dust-resilient sensing, and multi-site planning through short hops. Operational experiences from *Hayabusa*, *Hayabusa2*, and *OSIRIS-REx* have demonstrated both the risks and benefits of this coupling.

4.2 | Sampling–Anchoring Coupling

This coupling reveals a trade-off between anchoring force and the mass budget, particularly under uncertain surface conditions [127]. Reaction forces generated during drilling, coring, brushing, or grasping are transmitted to the anchoring system. If the anchoring force is insufficient—or if the anchor fails to engage with hard crusts or smooth rocks—microgravity can amplify rebound and drift, as evidenced by Philae's anchoring failure on comet 67P [128].

Strong anchoring, in contrast, enables larger sample volumes and deeper subsurface acquisition, while improving tool efficiency and operational stability. Design strategies emphasize multimodal anchoring mechanisms (mechanical, adhesive, and magnetic), redundancy and adaptive switching, preload or active push off before tool engagement, and real-time force/torque monitoring with overload retraction. The *MMX* dual-mode anchoring concept illustrates the shift from brittle mechanical anchors toward adaptive, bioinspired approaches [67].

4.3 | Mobility–Anchoring Coupling

The interaction between mobility and anchoring is fundamental to ensuring stability during slope traversal and extended observations. Failures often result from poor synchronization between anchor placement and body movement, unreliable grasp on irregular terrain, or release errors, potentially causing rollover or mission abort. When properly coordinated, however, anchors can serve as "temporary feet," enabling climbing, obstacle negotiation, and long-duration station-keeping where wheels or tracks are inadequate [129].

To address these, mitigation strategies involve redundant anchor systems with health monitoring, compliant micro-spine arrays, and closed-loop site selection combining geometric, textural, and force information [130]. Representative developments include NASA's ATHLETE concept, micro-spine climbing mechanisms, and bioinspired toe pad prototypes.

4.4 | Sampling–Mobility–Anchoring Coupling

The sampling–mobility–anchoring coupling is the interaction between the three subsystems that govern the overall stability and performance of small-body surface operations. When sampling, mobility, and anchoring are engaged concurrently, the

TABLE 9 | Coupling matrix of sampling-mobility-anchoring.

Coupling mechanism	Conflicts and risks	Synergies and benefits	Design levers/Mitigation strategies
Sampling–mobility	Contact or jet-induced rebound, loss of attitude, impulses exceeding escape velocity, and perception degradation by dust plumes	Short-duration contact with rapid retreat reduces risk and hopping/short relocations improve spatial representativeness	Compliant and force-limited end-effectors, closed-loop descent with plume-aware estimation, dust mitigation sensing, and risk-aware multi-site planning with short hops
Sampling–anchoring	Insufficient anchoring leading to rebound/drift, failure to penetrate hard crusts or smooth rocks, and destabilization from drilling torque	Enables large sample mass and deeper coring and enhances contact stability and tool efficiency	Multimodal anchoring (mechanical + adhesive/magnetic), redundancy and adaptive switching, preload or active push off, and force/torque monitoring with overload retraction
Mobility–anchoring	Unlock failures or slip causing rollover, uncertain grasp on rough terrain, and misaligned timing between placement and body movement	Enables stable locomotion and long-duration observations on slopes or rugged terrain and anchor-assisted locomotion as "hand–foot" synergy	Redundant anchors with health monitoring; compliant micro-spine arrays; and closed-loop anchor site selection fusing geometry, texture, and force data
Sampling–mobility–anchoring	Poor synchronization among sampling, mobility, and anchoring and forces transmitted through all subsystems causing instability or misalignment	Enables coordinated actions for efficient and robust sampling operations and improves system flexibility and adaptability to unpredictable terrain	Integrated feedback loops coordinating sampling, mobility, and anchoring; multimodal actuation and adaptive control systems; and real-time sensor fusion for force, movement, and environmental feedback

forces and moments generated by each subsystem propagate through the robot–surface interface and affect the others. Without proper coordination, such cross-coupling can introduce instabilities, with the primary risks stemming from misalignment and poor synchronization among subsystems, leading to slip, rebound, attitude disturbance, or localized overload. These effects can ultimately degrade operational efficiency and reliability.

A central technical challenge is load matching. If the forces and moments induced by sampling or locomotion exceed the holding and stability margins provided by the anchoring strategy, system-level failure modes—such as detachment, uncontrolled rebound, or loss of attitude control—may occur. Conversely, suboptimal load allocation can reduce overall efficiency, for example, when the anchoring subsystem operates near its limit while the sampling or mobility subsystems remain underutilized, resulting in conservative operations or premature termination.

Mission examples like *Hayabusa2* and *OSIRIS-REx* show how rebound and slippage during sampling can be exacerbated by the mobility system. Philae's anchoring failure on comet 67P highlights the critical need for better coupling between sampling and anchoring to maintain stability in unpredictable environments.

To mitigate these risks, effective system-level strategies include integrated feedback architectures that synchronize sampling, mobility, and anchoring in real time, as well as sensor fusion and adaptive control to regulate contact forces and moments dynamically. Multimodal actuation, such as combining wheels, legs, or spines, can broaden the operating envelope across heterogeneous terrains, while redundancy and fail-safe mechanisms enhance mission robustness by providing fallback options when a subsystem underperforms or fails.

4.5 | Control

In small-body surface operations, control systems face distinct challenges arising from microgravity, highly heterogeneous terrain, and limited onboard resources. In particular, coordinated control of sampling, mobility, and anchoring is essential for maintaining system stability and achieving efficient operations.

For sampling control, local soil properties and boulder distributions are often uncertain, making it difficult to predefine force control parameters. Moreover, the narrow allowable contact force window in microgravity means that small force or impulse deviations can induce attitude disturbances, creating a direct trade-off between stability and sampling efficiency. These difficulties are further compounded by constraints in onboard

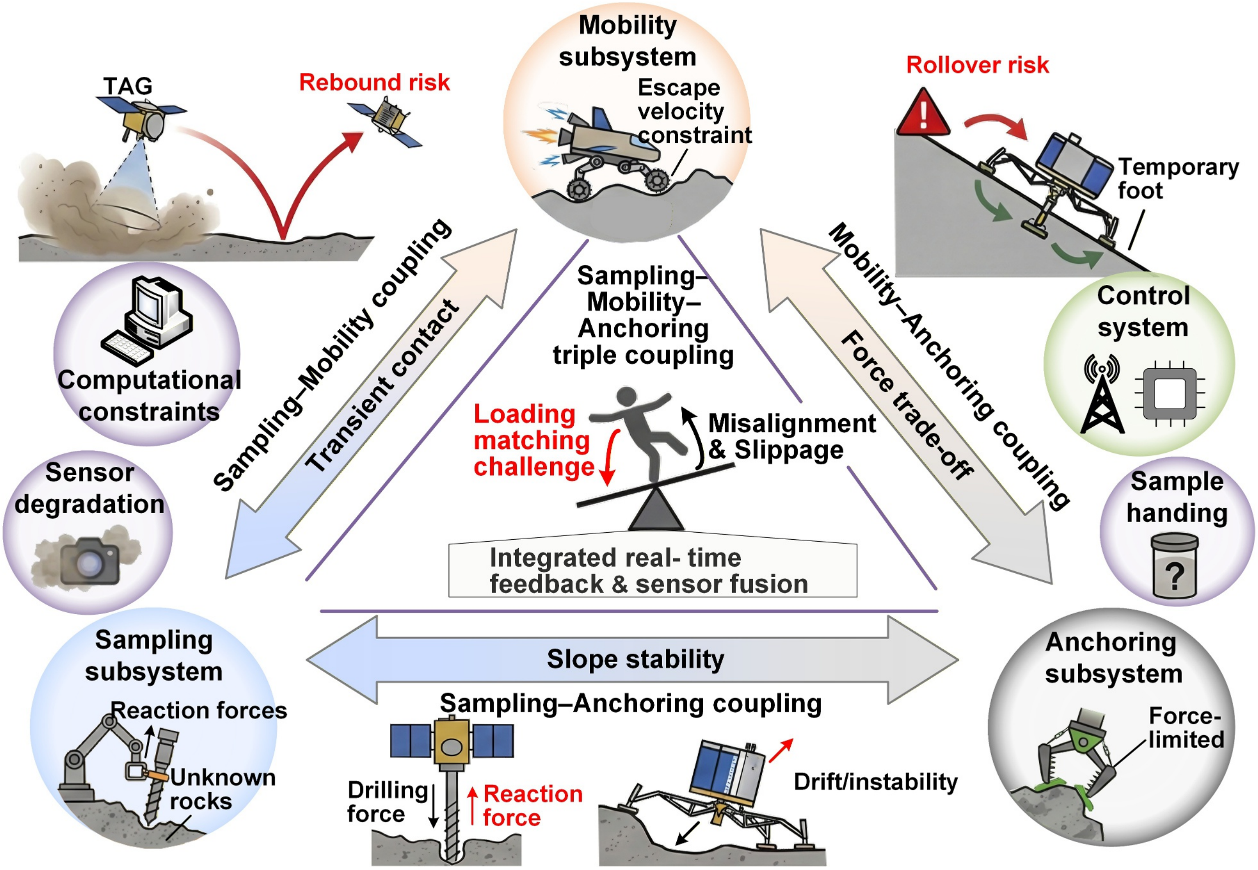

FIGURE 10 | The coupled dynamics and challenges of small-body surface operations.

sensing and computation, which can limit the bandwidth and robustness of real-time force/impedance feedback.

For mobility control, irregular terrain and time-varying environmental conditions—such as illumination changes and temperature fluctuations—can degrade perception quality and impose additional power management constraints. Under limited onboard computational capacity, mission planners must balance real-time path planning, local obstacle avoidance, and trajectory optimization, while maintaining responsiveness and energy efficiency.

Anchoring control is especially difficult in microgravity, as the lack of sufficient normal force makes it challenging to match anchoring forces to the surface's load-bearing capacity, particularly on uneven surfaces. Additionally, the reaction forces generated during anchoring can lead to attitude instability, especially when other actions are performed. To maintain stability, precise force–displacement coordination and attitude control are required after anchoring.

Addressing these challenges requires robust and adaptive control architectures. Integrated feedback frameworks can synchronize sampling, mobility, and anchoring in real time, while sensor fusion supports more reliable state estimation and contact force regulation under uncertainty. Multimodal actuation, such as combining wheels, legs, or spines, can broaden the operating envelope across diverse terrains, and redundancy with fault-tolerant strategies can further enhance reliability during complex, long-duration tasks.

4.6 | Ground–Space Domain Gap and Validation Pathway

A substantial portion of the evidence base for small-body sampling robots is generated through ground-based simulation and testing. However, the constraints that dominate operations in the real small-body environment cannot be captured through one-to-one replication of terrestrial conditions. The most fundamental domain gap arises from microgravity contact dynamics. Low gravity significantly reduces normal force and passive stabilization, weakens traction, and makes the system highly sensitive to contact impulse while tightening the allowable momentum exchange margin. Under these constraints, small variations in approach state, contact timing, and regolith response can be amplified into pronounced rebound, attitude disturbance, and post-contact drift. This amplification directly affects the controllability of sampling, mobility, and anchoring, as well as the continuity of the end-to-end mission chain. Meanwhile, uncertainty in regolith mechanics and local morphology further increases outcome dispersion, implying that locally repeatable ground results must be reinterpreted through mission-limiting conditions when translated to flight.

Accordingly, the transition from ground verification to space deployment is better viewed as a validation-to-flight pathway whose core objective is to align constraints and boundaries rather than to replicate the full environment. This pathway typically begins with physics-based modeling and uncertainty analysis to identify dominant sensitivities, followed by scaled or equivalent experiments that validate key mechanisms and failure modes. System-level integration tests and hardware-in-the-loop campaigns are then required to evaluate cross-module coordination, contact event management, and recovery behaviors. To enable comparability across stages, ground test reporting should follow flight evaluation logic: mission-driven metrics should be used to map ground observables to flight safety margins and performance boundaries, rather than treating ground outcomes as directly equivalent to in-space behavior.

To support comparability and transferability across validation stages, Table 10 presents a ground-to-flight benchmarking matrix that maps key performance quantities in sampling, mobility, and anchoring onto mission constraints and safety boundaries. The matrix is built upon observables that can be directly measured or reliably inferred in ground tests, including contact impulse and its dispersion, attitude disturbance responses during contact, post-contact drift and slip evolution, the controllable contact window and timing error, anchoring engagement and release reliability characteristics, reaction-load capacity and stability boundaries, fault recovery and reattempt capability, and end-to-end mission chain success rate. The benchmarking logic emphasizes mission-driven normalization and statistical reporting: contact impulse, attitude error, and angular rate responses are normalized by allowable mission limits and reported as distributions with exceedance probabilities; drift and slip are normalized by safe standoff distances or keep out boundaries and reported as boundary violation probabilities over a fixed time horizon; the mission-defined contact window is used as the success criterion while abort trigger frequency and recovery behavior are quantified; anchoring engagement and release are reported under bounded surface uncertainty in terms of success rate, worst-case behavior, and residual force or latency risks; and high-reaction operations are evaluated by normalizing stability margins and instability thresholds against planned tool loads. With this unified benchmarking framework, ground evidence can be interpreted under a consistent mission-relevant rubric, enabling system-level selection and risk trade-offs and providing traceable support for building the evidence chain from mechanism validation to flight deployment.

4.7 | Others

In addition to the three pairwise couplings, mission success is affected by several crosscutting constraints. First,

TABLE 10 | Ground-to-space performance benchmarking.

Benchmark metric	Ground observable	Flight benchmarking interpretation
Contact impulse controllability	Mean/dispersion of contact impulse and impulse tracking error	Normalize by allowable mission impulse limit and report impulse distribution and exceedance probability linked to escape safety margin
Attitude disturbance during contact	Peak attitude error, peak angular rate, and settling time	Normalize by allowable attitude/rate limits and report peak and integral deviation over the contact window linked to usable operation time
Post-contact drift/slip	Drift distribution, slip distance, and drift rate	Normalize by safe standoff distance or keep out boundary and report drift distribution over a fixed horizon and boundary violation probability
Controllable contact window	Achievable controllable contact duration, timing jitter, and abort triggers	Evaluate success within the mission-defined contact window, report timing error, and abort trigger frequency
Anchoring engagement reliability	Engagement success rate, engagement time, required preload, and failure modes	Report success under bounded surface uncertainty and worst case conditions and provide a proxy for holding stiffness or load capacity
Anchoring release reliability	Release success rate, release time, sticking events, and residual force	Evaluate against safe retreat requirements, report residual force distribution, and recontact risk induced by release latency
Reaction-load tolerance	Maximum sustained force/torque, stability boundary curve	Normalize by planned tool loads and report stability margin and threshold to loss of stability linked to feasible operation types
Fault recovery and reattempt capability	Recovery success rate, recovery time, and performance change after reattempt	Evaluate mission chain continuity and report recovery triggers and the degradation of key metrics after reattempt
End-to-end mission-chain success	Success rate for approach–contact–operation–retreat and dominant failure modes	Report end-to-end success under bounded uncertainty and map dominant failure modes to mitigation strategies

environmental perception is influenced by factors such as illumination, temperature, and dust plumes, which affect localization and navigation accuracy. Low-texture terrain and dust flow lead to sensor instability, complicating high-precision map building and real-time localization. The absence of GNSS-like infrastructure and visual inertial drift limits the reliability of TAG and hopping operations [131]. Mitigation relies on multimodal sensing fusion, robust estimation frameworks, plume-aware modeling, and terrain memory for relocalization [132, 133].

Second, sample handling and ISRU readiness remain underdeveloped, with dust contamination and sealing issues potentially causing leakage or cross-contamination. Current countermeasures include dust-tolerant sealing, electrostatic mitigation, and staged ingest–meter–store architectures [29, 134].

Lastly, in deep-space missions, communication latency and limited bandwidth demand that control systems have strong autonomous decision-making capabilities to ensure that complex tasks can be performed and system failures can be managed within the available resources [135].

5 | Future Development Trends and a Technical Road Map

As small-body exploration advances toward longer duration and higher risk surface operations, future breakthroughs in sampling, mobility, and anchoring will be increasingly driven by system-level co-design rather than isolated improvements in individual subsystems. Under microgravity, irregular topography, and highly uncertain surface properties, mission robustness depends on the ability to acquire samples while maintaining stability, managing reaction loads, and guaranteeing safe retreat and relocation. Accordingly, as illustrated in Figure 11, this section summarizes anticipated developments in the three core modules—sampling, mobility, and anchoring—then discusses their integrated synergy, and finally highlights two crosscutting enablers: modular lightweight architectures and AI-powered autonomy.

5.1 | Diversified Sampling Technology

Sampling will evolve toward diversified and configurable acquisition to cope with the wide variability of small-body surfaces, ranging from loose regolith to gravel-rich layers and locally hardened crusts. Future systems are expected to integrate multiple acquisition modes within a unified sampling suite, including short-contact collection, noncontact or minimally intrusive collection where direct interaction is risky, and drilling/coring for subsurface access. Such multimodal sampling expands the accessible material spectrum and improves sample representativeness across heterogeneous terrains. At the subsystem level, emphasis will shift to reducing sensitivity to uncertain contact conditions by incorporating compliant interfaces, controllable interaction loads, and stable retention/transfer pathways that preserve sample integrity during withdrawal and subsequent handling. Multi-point and multidepth acquisition will become more common as sampling mechanisms are designed to support repeated operations across sites while maintaining consistent performance.

Furthermore, as small-body missions extend beyond science-driven sample return toward resource prospecting and in situ resource utilization, sampling technologies are expected to evolve from low-throughput, event-based collection tools into front-end units for scalable extraction. In this context, future systems will emphasize high throughput, sustainability, and low reaction-load operations by forming an integrated chain of material liberation–collection–transport–temporary storage. Energy-driven fragmentation and loosening methods are likely to play an enabling role. For instance, electromagnetic pulse fragmentation can induce rapid rock breakage through short-duration energy injection with limited sustained mechanical contact, enabling a "liberate first, collect later" pathway for competent crusts or boulders. This approach reduces reliance on

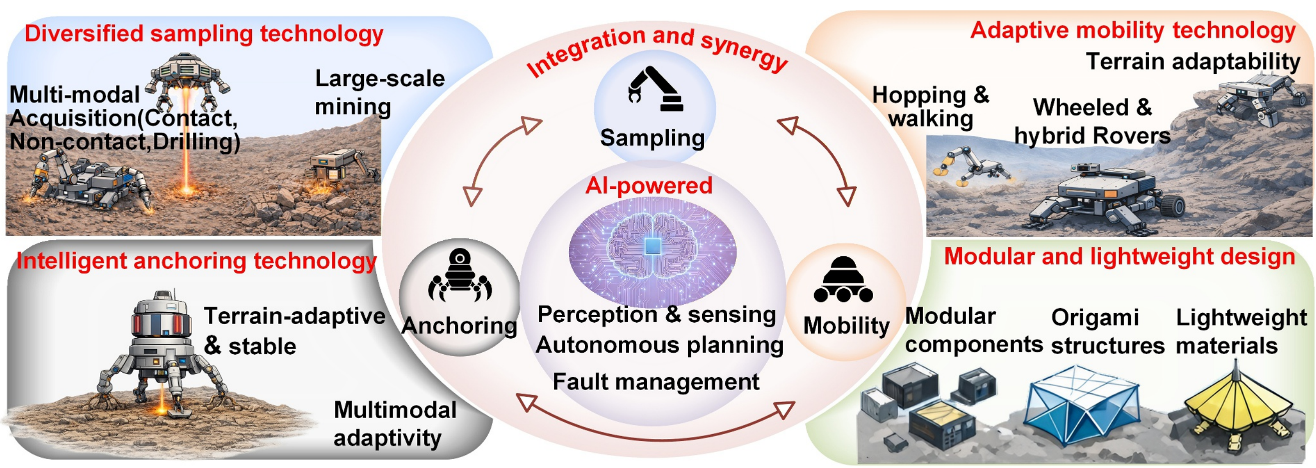

FIGURE 11 | Future development trends and a technical roadmap.

prolonged push off forces or high-torque drilling that could destabilize the platform in microgravity.

5.2 | Adaptive Mobility Technology

Mobility will increasingly rely on adaptive and hybrid locomotion to address low gravity, weak traction, and rugged microtopography that limit conventional wheeled traversal. Future platforms are expected to expand beyond purely wheeled designs toward combinations of hopping, crawling, and legged or reconfigurable mechanisms, enabling robots to negotiate boulder fields, steep slopes, and highly discontinuous terrain. A key trend is the ability to transition between locomotion modes to trade speed for stability when needed and to maintain controllability when the local contact state is uncertain. In parallel, mobility design will place greater emphasis on stability margins and energy efficiency across repeated maneuvers, ensuring that relocation and short-range repositioning remain feasible even under constrained power budgets and thermally varying environments.

5.3 | Intelligent Anchoring Technology

Anchoring will move toward intelligent, multifunctional, and terrain-adaptive solutions that extend beyond single-mode mechanical penetration. Future anchoring systems are expected to combine mechanical, adhesive, and bioinspired concepts to achieve reliable attachment across surfaces with widely varying hardness, roughness, and particulate contamination. The central requirement is to establish stable contact and holding capacity without overreliance on favorable surface conditions or large normal forces that are inherently limited in microgravity. Intelligent anchoring will increasingly emphasize reliable engagement and controllable release, as well as the ability to maintain stability while other subsystems generate reaction loads. Multimodal concepts, exemplified by mission-ready developments, such as *MMX* and *Tianwen-3* anchoring approaches [136–138], illustrate the broader shift toward anchors that can adapt their attachment strategy to local conditions and operational phases, thereby improving robustness for future small-body missions.

5.4 | Integration and Synergy of the Three Core Modules

Rather than operating as independent subsystems, sampling, mobility, and anchoring will be co-designed as a coupled system whose overall performance is determined by coordinated interaction with the surface. In future missions, mobility is expected to provide controlled positioning and retreat capability around sampling events, while anchoring will supply stability and load paths that prevent rebound, drift, or attitude excursions during contact and tool actuation. Conversely, sampling strategies will be increasingly formulated with explicit consideration of mobility constraints and anchoring capacity, ensuring that interaction loads remain compatible with the system's ability to maintain posture and recover safely. This integration favors closed-loop operational sequences in which the robot can approach, stabilize, acquire material, and retreat with bounded risk, enabling repeated operations across multiple sites and improving both mission efficiency and scientific yield.

5.5 | Modular and Lightweight Design

Modularity and lightweight design provide a key engineering pathway for realizing multimodal capabilities and system-level synergy. A modular architecture enables sampling heads, anchoring end-effectors, and locomotion units to be replaceable and upgradable, allowing the platform to be reconfigured for different targets and mission objectives while improving cross-mission reuse and cost-efficiency. Lightweight structures and highly integrated mechatronic units reduce launch and operational burdens, freeing mass and power margins for sensing, redundancy, and reliability enhancement. Moreover, origami-inspired structures offer a structural route featuring high packing efficiency, deployable expansion, and shape reconfigurability, enabling functional scalability under stringent stowage volume and mass constraints [139]. Overall, combining modular lightweight architectures with origami-based structures can enhance deployability, reconfigurability, and mission adaptability without significantly increasing system complexity, providing a cost-effective engineering solution for complex and long-duration surface operations.

5.6 | AI-Powered Autonomy

AI-powered autonomy is a crosscutting enabler that links perception, decision-making, and control across sampling, mobility, and anchoring and is therefore essential under deep-space communication latency and bandwidth constraints. Autonomy is not a single function but a layered capability stack, typically comprising onboard perception and state estimation, risk-constrained planning and task sequencing, and closed-loop execution with monitoring and failure recovery. As these layers mature, reliance on real-time ground intervention can be further reduced while maintaining verifiable safety margins under strong environmental uncertainty.

At the level of navigation and hazard avoidance, Mars rover missions have established reusable engineering paradigms. For example, *Perseverance*'s AutoNav uses onboard vision to build local 3D terrain understanding, identify hazards, and select safe paths, improving driving efficiency within limited communication opportunities. Earlier rover missions likewise validated core components such as visual odometry and autonomous obstacle avoidance, consolidating a practical pipeline for robust localization, short-horizon planning, and safe execution under constrained onboard computation. For small-body contact operations, *Hayabusa2* enabled high-precision terminal guidance and touchdown window control via artificial markers and image-based onboard navigation, highlighting the reliance on safety-critical autonomy during terminal phases. Overall, existing missions demonstrate the feasibility of onboard navigation and safety-constrained control in critical phases, while microgravity dynamics and uncertain contact processes are pushing autonomy beyond "local navigation intelligence" toward "task-chain closed-loop autonomy".

Compared with large-body rover exploration, small-body surface operations place greater emphasis on microgravity dynamics, short interaction windows, and tightly coupled constraints among sampling, mobility, and anchoring. Current research is strengthening perception against low texture, rapid illumination changes, and dust–plume interference via multi-modal fusion and robust estimation, supported by simulation-to-test validation and hardware-in-the-loop campaigns. Planning is increasingly framed as uncertainty- and risk-aware decision-making that balances scientific return, operational risk, and energy cost and generates action sequences with enforceable safety envelopes for TAG, anchoring, and tool–surface contact. Integrated co-planning and coordinated control for coupled sequences—approach, stabilization, anchoring, sampling, retreat, and relocation—are being explored through hybrid frameworks that combine learning-based adaptation with physics-based constraints to improve generalization while preserving verifiability. In parallel, multi-robot autonomy is being investigated for distributed scouting, shared mapping, and coordinated sampling logistics.

Despite progress, autonomous decision-making for small-body surface operations still faces three fundamental challenges. First, environmental and interaction uncertainty is extreme: bearing strength, cohesion, and particle-size distributions are rarely known a priori, and identical actions can yield markedly different contact responses across micro-regions. Second, safety margins are tight and strongly coupled: allowable impulse, attitude deviation, and slip margins are limited in microgravity, and reaction loads can cascade across modules, requiring autonomy to manage coupled constraints rather than optimize subsystems in isolation. Third, resources and verification remain limiting: onboard computation, sensing bandwidth, and energy budgets constrain complex models and high-rate control, while flight systems demand interpretable logic and systematic validation to ensure controllable failure modes and recovery under domain shifts.

In the longer term, autonomy will evolve from local navigation intelligence toward mission-level coupled decision-making and tighter integration with health management, where diagnostics and prognostics inform planning and scheduling to improve long-duration productivity and reliability. Multi-robot cooperation will likewise become an important path to increase coverage and reduce single-point failure risk, strengthening robustness for complex small-body operation chains.

5.7 | Applicability and Challenges for Rapidly Rotating and Active Small Bodies

Future small-body missions will increasingly target objects whose physical properties are only partially constrained prior to arrival. Compared with the relatively well-characterized, slowly rotating targets that dominate current flight heritage, poorly observed bodies may exhibit rapid rotation, strong shape irregularity, and time-varying surface activity. Under such conditions, the operational environment becomes more dynamic and the available interaction margin narrows. The effective contact window can be shortened by fast local surface motion and evolving illumination and geometry, while microgravity makes the system highly sensitive to even modest contact impulses. As a result, small deviations in approach state, surface response, or local terrain can produce disproportionate rebound, attitude disturbance, and post-contact drift, increasing the likelihood of degraded control authority or unintended departure. These characteristics imply that existing systems should be assessed not as a single nominal capability but in terms of an applicability envelope defined by allowable momentum exchange, controllable contact duration, and robust recoverability under uncertainty.

In this regime, sampling, mobility, and anchoring become more tightly coupled through shared momentum management and contact-stability requirements. Sampling concepts that require sustained contact or large reaction loads carry elevated risk because rapid rotation, and activity-driven disturbances reduce the time available to establish stable constraints and increase variability in regolith response. Mobility modes that rely on traction and predictable ground reaction forces are more likely to experience slip, reduced steering authority, and heightened sensitivity to terrain heterogeneity. Ballistic relocation can expand reach, but it amplifies uncertainty in landing outcomes when restitution behavior is poorly bounded. Anchoring faces similar challenges: Engagement quality depends on uncertain local strength, morphology, and dust contamination, and failed engagements may be difficult to recover when operational windows are short. Consequently, design priorities shift from maximizing single-module performance to ensuring mission-chain robustness, emphasizing conservative impulse management; predictable contact dynamics; and rapid, reliable, disengagement, and retreat strategies that preserve escape safety.

These considerations suggest that existing technical approaches remain relevant but should be reconfigured for robustness in dynamic, uncertain environments. A practical direction is to favor interaction modes that reduce exposure time while maintaining controllability, supported by tighter closed-loop guidance, explicit contact event management, and anchoring concepts that prioritize reversible engagement and fault-tolerant recovery. Stronger autonomy is also required to cope with limited prior knowledge and time-varying conditions, with onboard perception and state estimation continuously updating local constraints and enforcing risk-aware decision logic. Overall, extending operations from known, slowly rotating bodies to poorly characterized, rapidly rotating, or active targets will depend less on introducing entirely new mechanisms than on system-level co-designs and that explicitly budgets momentum, constrains contact duration, and preserves recoverability across sampling, mobility, and anchoring.

6 | Conclusion

Small-body sampling robots are a key enabling platform for both planetary science and in situ resource utilization. Their success is ultimately determined by the ability to achieve controlled surface interaction under microgravity, uncertain regolith mechanics, and mission-critical operation sequences. This review has presented a unified, system-oriented synthesis centered on three core modules—sampling, mobility, and anchoring. It summarizes the evolution of representative missions and mechanisms and compares major design trade-offs in terrain applicability, reaction-load management, technology readiness, and system cost. More importantly, it highlights that many persistent bottlenecks do not arise from any single subsystem in isolation, but from the dynamic coupling among the three modules, where contact impulses, attitude disturbances, anchoring capacity, and retreat maneuvers can amplify one another across the operational chain.

The analysis indicates that flight heritage has validated the robustness of "short-contact and rapid retreat" paradigms, such as TAG-based interactions combined with hopping or short relocations, yet these approaches remain constrained in sampling depth and throughput. Future missions that demand higher representativeness and sustained productivity must progress from "mechanism feasibility" to "task-chain sustainability," enabling repeated multi-site and multi-depth operations with verifiable safety margins and reliable sample handling. Accordingly, sampling systems are expected to evolve from single-mode tools toward diversified, configurable suites and for resource-oriented scenarios, further toward scalable front-end workflows integrating material liberation, collection, transport, and temporary storage. Mobility will increasingly rely on hybrid and switchable locomotion to balance efficiency and stability across heterogeneous terrains. Anchoring will move beyond brittle single-mode penetration toward multimodal, switchable, and releasable solutions that can provide repeatable constraint across crusted, blocky, and dust-contaminated surfaces.

From an engineering perspective, two crosscutting enablers are emphasized. First, modularity and lightweighting provide a practical pathway to system synergy, supporting replaceable and upgradable sampling heads, anchoring end-effectors, and mobility units, while freeing mass and power margins for sensing, redundancy, and reliability enhancement. In addition, origami-inspired deployable structures offer an effective structural route for high packing efficiency, functional expansion after deployment, and shape reconfigurability under stringent volume and mass constraints. Second, AI-powered autonomy will serve as an enabling layer that closes the perception–decision–control loop under deep-space latency and bandwidth limits, pushing capability from local navigation intelligence toward task chain–coupled autonomy, with growing integration of fault recovery, health-aware decision-making, and multi-robot cooperation.

Finally, as target bodies extend beyond well-characterized objects to faster rotating, more active, and less predictable environments, mission feasibility will increasingly depend on a clearly defined operability envelope—including momentum-exchange limits, admissible contact windows, and recoverability boundaries. Future research and system design should therefore prioritize system-level co-design and traceable verification evidence, focusing on impulse budgeting, contact event management, anchoring–tool load matching, rapid and reliable disengagement, and closed-loop validation through reduced-gravity and hardware-in-the-loop campaigns. Such a pathway system will support longer duration, higher frequency, and ultimately more economically viable deep-space surface operations and resource-oriented missions.

Author Contributions

Yurui Shen: writing – original draft, writing – review and editing, visualization. **Yixin Zhu:** data curation, investigation. **Mingxia Bao:** data curation, investigation. **Ting Zhang:** methodology, funding acquisition. **Jun Wu:** methodology, formal analysis. **Jingbin Hao:** supervision, validation. **Dezheng Hua:** funding acquisition. **Xinhua Liu:** conceptualization, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

The data are available from the corresponding author on request.

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