Free-Flying Intra-Vehicular Robots: A Review

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***Abstract*—Intra-vehicular free-flying robots have been operating inside the International Space Station (ISS) for over two decades. With the launching of the Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) free-flyer in 2003, there have been a total of six free-flying robots aboard ISS. These free-flyers include SPHERES, the Internal Ball Camera (Int-Ball), Crew Interactive MObile companioN (CIMON), Astrobee, Crew Interactive MObile companioN-2 (CIMON-2) and Internal Ball Camera 2 (Int-Ball2). Intra-vehicular free-flyers have expanded space robot capabilities in habitat inspection, terrestrial K-12 education outreach, microgravity research and development (R&D), and other intra-vehicular activities (IVA) in microgravity. This survey paper provides a comprehensive review of these six ISS intra-vehicular free-flying robots including their initial development details, intended Concept of Operation (ConOps), high-level system overview, microgravity R&D efforts, and contribution to the space robotics state-of-the-art. This paper will then cover some of the unanswered research questions for the development of future free-flyers. As future space stations emerge into new on-orbit destinations, the next-generation of free-flyers will build on the capabilities of these six ISS intra-vehicular free-flying robots and expand into novel areas of IVA.**

***Index Terms*—Free-flying robots, intra-vehicular, IVA, ISS, SPHERES, Int-ball, CIMON, Astrobee, CIMON-2, Int-Ball2.**

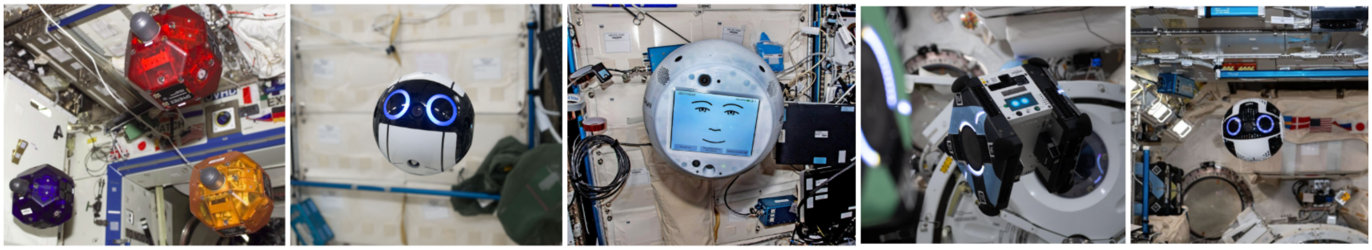
I. Introduction

Since 2003, intra-vehicular free-flying robots have been aboard the International Space Station (ISS) performing a variety of intra-vehicular activities (IVA) such as habitat monitoring, crew interaction, and microgravity research and development (R&D) [1]–[5]. There have been a total of six intra-vehicular free-flyers launched to ISS starting with the Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) free-flyer in 2003 [6], [7]. Since then, five additional free-flyers have flown to station, including the Internal Ball Camera (Int-Ball), Crew Interactive MObile companioN (CIMON), Astrobee, Crew Interactive MObile companioN-2 (CIMON-2) and most recently the Internal Ball Camera 2 (Int-Ball2) [3], [8]–[11]. Each free-flyer has its own robotic systems and capabilities in computation, vision, power distribution, and manipulation to answer unique research questions under microgravity conditions [12]–[15].

The free-flyer state-of-art has evolved overtime, based on lessons learned from previous ISS free-flyers. An example of such free-flyer succession includes the Japanese Aerospace Exploration Agency's (JAXA) Int-Ball to later development of Int-Ball2, and the National Aeronautics and Space Administration's (NASA) SPHERES to Astrobee development [16]. The six ISS intra-vehicular free-flying robots were developed by various institutions in space robotics ranging from industry to academia with collaboration with government space agencies around the world. In chronological order, the list below highlights the six ISS intra-vehicular free-flyers flown on station. Fig. 1a-1e also shows five of these six free-flyers:

1) *SPHERES*
   Flown in 2003, the SPHERES were developed by the Massachusetts Institute of Technology (MIT) as a testbed to research novel satellite formation flights, docking, and rendevzous on ISS. They were the first look at a free-flying platform on ISS and free-flying robots with NASA's Smart SPHERES. [**?**]
2) *Int-Ball*
   Flown in 2017, the Japan Aerospace Exploration Agency's (JAXA) Int-Ball was the first free-flyer with advacned vision capabilities for photography, videography, and teleobservation from ground on the Japanese Exploration Module (JEM) or "Kibo" on ISS.
3) *CIMON*
   Flown in 2018, CIMON was primarily developed by the Deutsches Zentrum f¨ur Luftund Raumfahrt (DLR) and Airbus Defense and Space to test the capabilities of artificial intelligence (AI) in free-flying robots on station. CIMON was made with a graphical user interface (GUI) to perform studies on human-robot interaction in space.
4) *Astrobee*
   Flown in 2019, NASA's Astrobee is a free-flying robot in the JEM for testing a variety of hardware and software payloads for their guest science program (GSP) and was made to assist crew in daily station tasks.
5) *Int-Ball2*
   Flown in 2023, Int-Ball2 is JAXA's successor to Int-Ball with increased vision and computation capabilities.

This survey paper presents a comprehensive review of all the intra-vehicular free-flying robots including their development details, intended concept of operations (ConOps), robotic system overview, supported microgravity research and development (r&d). This survey will then conclude with open challenges and opportunities for future free-fliers given lessons learned from the current state-of-the-art in space robotics.



(a) (b) (c) (d) (e)

Fig. 1. All five free-fliers aboard the ISS in chronological order from left to right. 1a: SPHERES (photo credits: NASA/MIT SSL), 1b: Int-Ball (photo credits: JAXA, 1c: CIMON (photo credits: Airbus), 1d: Astrobee (photo credits: NASA), 1e: Int-Ball2 (photo credits: JAXA)

II. SPHERES

The SPHERES were developed by the Massachusetts Institute of Technology's (MIT) Space System Laboratory (SSL) in their Department of Aeronautics and Astronautics. SPHERES' development costs were primarily funded by the Defense Advanced Research Projects Agency (DARPA), National Aeronautics and Space Administration (NASA) and Aurora Flight Sciences. Developed in the late 1990's into the early 2000's, this collaborative r&d effort was designed to test and validate novel spacecraft guidance, navigation, and control (GNC) algorithms for satellite formation flying, rendezvous and on-orbit docking. A multi-SPHERES free-flying formation can be seen in Fig. 2 below.

Fig. 2. Three SPHERES free-fliers aboard the ISS. (photo credits: MIT SSL)

Some of these satellite algorithms were developed for relative attitude control, station-keeping, retargeting, image plane filling maneuvers, collision avoidance, propellant balancing, array geometry estimators, and docking control architectures for novel formations. SPHERES could be used as a testbed for these satellite algorithms in single-satellite formations or interaction between multi-agent systems. SPHERES as an ISS testbed could allow NASA and other satellite developers to rapidly create and validate their algorithms, which could change the way satellite software was developed. In practice, multi-SPHERES formations would be initialized by crew to position each SPHERES in location to test different satellite GNC algorithms. These algorithms could then be applied to high-risk defense satellites or constellations with precise docking. SPHERES' ConOps positioned it to be a low-cost long-term ISS testbed for microgravity GNC validation.

These 18-sided polyhedron volleyball-sized free-fliers propelled through the ISS using compressed CO_2 tanks and replaceable 12V AA batteries for safe, rapidly-repeatable, and crew-in-the-loop testing on station. SPHERES was capable of repeatable ISS experiments, but with a short time for flight, SPHERES required crewtime for battery and CO_2 swapping for long-duration and repeated ISS experiments. SPHERES used a suite of ultrasonic sensors and beacons onboard the SPHERES and along the walls of the ISS respectively to enable precise relative motion control and localization.

A. *SPHERES Guest Science Program*

SPHERES Guest Science Program (GPS) was an innovative approach to rapid microgravity r&d leveraging SPHERES' three stage testing approach [**?**]. Guest science users could test their experimental hardware and software payloads on SPHERES to validate their work in a realistic environment. The launching of the GSP lead to more than 40 microgravity experiments, ranging from microgravity rendezvous to docking procedures and formation flying. The SPHERES GSP followed a three-stage approach to testing on the ISS in the following order: SPHERES GSP Simulation, SPHERES Laboratory, then demonstration on SPHERES ISS. Starting with SPHERES GSP Simulation based in C++ and MATLAB, guest scientists could run their custom code in a simulation environment to test their algorithm prior to terrestrial testing. Guest scientists could then test their code on SPHERES in the SPHERES 3-Degrees-of-Freedom (DOF) Laboratory on Earth. Finally, flight software could be tested on the SPHERES ISS for 6-DOF realistic microgravity testing on the ISS. Fig. 3 shows the SPHERES GSP code development architecture and process which involved MIT's SSL and the ISS SPHERES.

B. *Smart SPHERES*

In 2011, NASA developed the Smart SPHERES prototype and flew it aboard ISS to test teleoperation capabilities. These Smart SPHERES were standard SPHERES equipped with smartphones for intelligent control, teleoperation, and real-time updates to ground-support. This marked the beginning

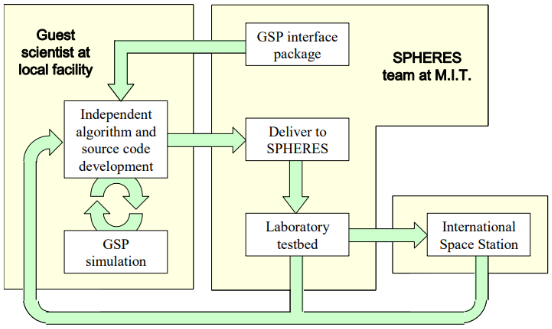


Fig. 3. SPHERES GSP novel code development architecture

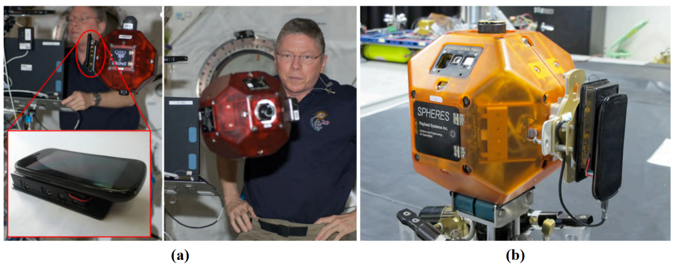


Fig. 4. 4a) Astronaut Mike Fossum testing a Smart SPHERES aboard the ISS with a highlighted image of the Nexus-S on the red SPHERES. 4b) Is a yellow SPHERES with a Nexus-S attached testing at the NASA Ames testing facility and granite table. (photo credits: NASA)

of free-flier robot development on ISS, in particular a 6-DOF platform on the ISS for mobility, testing, and operation in microgravity. These Smart SPHERES opened a realm of possibilities for r&d and unforeseen ISS activities such as STEM engagement.

Smart SPHERES' was comprised of a commercial smartphone (Samsung Nexus-S) as an embedded controller and upgrades in high-performance processor, significant on-board memory, color cameras, additional sensors (temperature, sound, gyroscopes, accelerometers), a touchscreen display, an Wi-Fi network. These Smart SPHERES was tested at NASA Ames Research Center on a free-flying testing facility on a granite lab.

C. SPHERES Zero Robotics

Beginning in 2009, SPHERES was also used for STEM outreach and education efforts on Earth through MIT's annual Zero Robotics (ZR) competition. ZR challenged middle and high school students in the United States to code and compete in algorithm development challenges, with finalists seeing their programs executed live aboard ISS. This educational engagement demonstrated the potential of free-flying robots not only as r&d testbeds, but also as platforms for public participation and student K-12 STEM engagement. It also served as a collaborative effort being ran by an academic institute (MIT) and funded by government space agency (NASA, ISS National Lab) and industry (Northrop Grumman, Aerospace Co.).

SPHERES ended operations in 2017 after more than a decade of successful missions on ISS. Despite its relatively simple hardware, the SPHERES laid foundational groundwork for subsequent intra-vehicular free-fliers by validating core robotic functions and capabilities in teleoperation and SHRI. Its lessons learned continued into the development of NASA's next-generation free-flier, Astrobee.

III. Int-Ball

The Japan Aerospace eXploration Agency (JAXA) developed their first intra-vehicular free-flying robot in the 2010s called the Internal Ball Camera (Int-Ball). Int-Ball was flown to the ISS' Japanese Experimental Module (JEM) or "Kibo" in 2017 and was ISS' second free-flying robot. Int-Ball was funded by JAXA's Human Spaceflight Directorate and Research and Development Directorate in collaboration with academic institutions like the University of Tokyo's the Artificial Intelligence (AI) Lab and industry partners in robotics and AI.

Int-Ball was developed as a low-cost free-flier equipped with state-of-the-art vision systems through onboard cameras to assist to reduce overall crew time in inspection tasks on the JEM by approximately 8% [**?**]. Int-Ball's complementary metal-oxide-semiconductor (CMOS) digital camera module and a high performance embedded CPU board with ARM Cortex-A9 allowed for wireless transmission at a HD resolution of 720p:1280×720 pixels, frame rate of approximately 10 to 30 frames per second (fps), and bitrate of about 16 kbps to 40 Mbps. Int-Ball's spherical-shape and lightweight components allowed it to free fly through ISS safely around the pressurized JEM using small electric fans for propulsion. Int-Ball was developed for autonomous control capabilities or teleoperation from the ground-based communication through wireless LAN connections. Equipped with a powerful camera for visual-inspection tasks of the JEM, and two USB connectors for power and data transfer, Int-Ball was the first of its kind intelligent free-flying robot which added vision onto the list of free-fliers capabilities on ISS. Fig. 5 shows Int-Ball's design and testing on JAXA's air carriage system.

Int-Ball's ConOps during development was to reduce crew-time in routine photography and videography in the JEM by autonomously capturing images and video of the module. This would be done using Int-Ball's main monitor camera and several onboard ultrasonic distance sensors as seen in Int-Ball's design in Fig. 5a. Int-Ball could transmit real-time visual data to ground control, to monitor onboard conditions without interrupting crew workflows, optimizing crewtime in the JEM. Int-Ball's developed marked a capability addition to ISS intra-vehicular free-fliers for increasing crewtime efficiency by reducing astronaut tasks.

Despite its limited mobility range and functional scope, Int-Ball demonstrated the operational feasibility of continuous robotic visual monitoring in microgravity. Its real-time communication link with ground control enabled remote commanding and opened up new modes of ground-crew collaboration. Additionally, its compact design and human-friendly appearance reflected JAXA's emphasis on seamless robotic integration in astronaut-occupied environments.

Int-Ball's deployment provided valuable insight into the design considerations for small, purpose-built IVA robots. Lessons learned from its performance informed the development of its successor, Int-Ball2, which aimed to improve flight stability, communication robustness, and sensor fidelity. Int-Ball represents a milestone in operational IVA robotics by validating the utility of persistent, autonomous visual monitoring in a crewed space habitat.

IV. CIMON

CIMON (Crew Interactive Mobile Companion) is the first voice-enabled, AI-powered intra-vehicular free-flier flown on station. Funded primarily by the Deutsches Zentrum für Luft- und Raumfahrt (DLR), Airbus Defence and Space (Airbus), International Business Machines Corporation (IBM), Ludwig Maximilian University of Munich (LMU) and German Federal Ministry of Economics and Energy (BMWi), CMON was launched in 2018. CIMON's initial ConOps were as a space technology flight demonstration focused on SHRI and AI in microgravity. The spherical free-flier is equipped with facial recognition, natural language processing (NLP), and a central display interface designed to support crew members by providing hands-free access to procedures, data retrieval, and real-time dialogue-based assistance. CIMON as a platform would assist crew in a different way through assistive verbal and display support, changing the game of SHRI. The soccer-ball sized free-flier was manufactured using a 3-Dimensional (3D) printing and is 32 centimeters in diameter. CIMON has twelve electric fans that allow it to freely free and rotate in any direction using these fans.

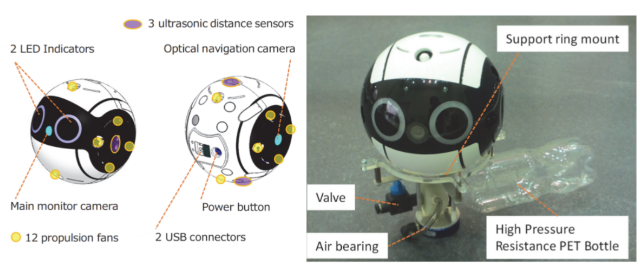
CIMON's various onboard hardware was designed to test the feasibility and effectiveness of emotionally intelligent assistive robots in isolated, confined, and extreme (ICE) environments. CIMON's onboard AI was built on IBM Watson to enable context-aware conversational interactions with crew, allowing CIMON to interpret voice commands, respond conversationally, and assist astronauts during ISS procedures. CIMON's increase in processing power, audio speaker and retrieval capabilities, and visual display represents a increase in free-flier capabilities for use in AI and SHRI.

CIMON contributed to the broader vision of integrating emotionally intelligent robots into human spaceflight operations, not just as testbeds, but as adaptive and assistive companions capable of responding to stress, reducing cognitive load, and enhancing psychological well-being during long-duration human spaceflight missions.

V. ASTROBEE

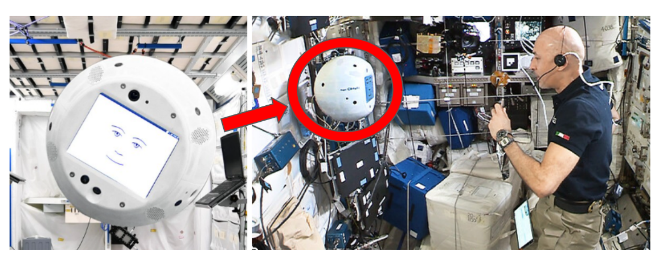
Astrobee is NASA's second intra-vehicular free-flying robot, teleoperating aboard JAXA's JEM on the ISS capable of supporting a range of microgravity IVA such as machine learning algorithms, manipulation payloads, guest science, and terrestrial STEM education. Developed by NASA in the 2010's to support a broad range of autonomous robotic operations in microgravity, Astrobee was primarily funded and developed by NASA's Game Changing Development (GDC) program under the Space Technology Mission Directorate (STMD). Developed out of NASA Ames Research Center's Intelligent Robotics Group (IRG), Astrobee launched to ISS in 2019. There were six Astrobees developed initial, three cube-shaped free-fliers named Honey, Queen, and Bumble sent to the ISS, and three Astrobees for on-Earth testing in the NASA Ames' Granite Lab Testing Facility. A picture of Astronaut Chris Cassidy interacting with Honey and Bumble on ISS can be seen in Fig. 7.

These 12.5 cubic inch volume cubes could be teleoperated within the JEM similarly to Smart SPHERES a few years prior. Astrobee built on the lessons learned from SPHERES, which ended shortly around the time of the start of the Astrobee program. Astrobee incorporating free-flying capabilities in robot autonomy, crew safety, and high processing robotic systems integration to provide a more modular, capable, and extensible system for more guest scientists and microgravity environments. Unlike SPHERES, which relied on compressed gas for propulsion, Astrobee uses electric ducted fans coupled with a recharging dock station for reusable and sustainable operation. This move towards electric propulsion, allowed for "crew-minimal" ISS operations and tasks, with complete teleoperation of Astrobees on station and longer duration repeatable testing. This free-flying architecture was translated



(a) (b)

Fig. 5. 5a) Int-Ball's front and rear computer aided design (CAD) includign onboard LEDs, sensors, USB connections, and propulsion fans. 5b) Int-Ball on a air carriage system. (photo credits: JAXA)



(a) (b)

Fig. 6. 6a)CIMON concept art of free-flying in a ISS environment 6b) CIMON interacting with Astronaut Luca Parmitano (photo credits: DLR and ESA)

Fig. 7. Astronaut Chris Cassidy holding Bumble and working with Bumble in the JEM. (photo credits: NASA)

to the the development philosophy similarly to SPHERES, whereas novel code could be first tested in simulation, then on a realistic terrestral 3-DOF testbed, and finally flown on station for microgravity testing.

Astrobee's modular systems allowed for expansion out of its original ConOps which lied in assisting crew with nominal tasks such as cargo transport and station upkeep. These additional capabilities in payload interfact enabled both autonomous and teleoperated tasks for supporting crew productivity, spacecraft maintenance, and microgravity hardware and software payload R&D. Astrobee's free-flying capabilities include autonomous navigation via visual-inertial odometry, localization and redocking, dexterous manipulation using a generic 3-DOF underactuated tendon-driven perching arm payload, and environmental sensing through multiple cameras and microphones. The system also features a docking and recharging station, allowing it to remain operational for extended periods without crew intervention for recharging.

Much R&D

This persistent autonomy allows Astrobee to perform repeated IVA tasks such as inventory monitoring, acoustic diagnostics, and visual inspection without burdening using crew time. These system designs were a giant leap in long-term autonomy in free-flying robots. Astrobee also emphasizes human-robot interaction and system safety, with multiple layers of fault tolerance, safety interlocks, and override protocols. Astrobee can also detect and respond to environmental constraints, such as approaching astronauts or operational boundaries, and autonomously reroute or pause activity to ensure safe coexistence. Its user interface includes both ground-based mission planning tools and tablet-based astronaut controls, allowing flexible command modalities that integrate with daily crew operations. These features reflect a systems-level design focus on interoperability and reliability in dynamic space environments.

A. *NASA Guest Science Program*

One of the defining aspects of Astrobee is its open software and hardware architecture, which enables modular development and user programmability. This flexibility supports NASA's version of the GSP, where guest scientists could, develop, and execute experiments using the Astrobee platform as a ISS testbed similar to the SPHERES GSP. Guest Science investigations have explored areas such as robot-robot coordination, visual serving, microgravity fluid dynamics, and AI-based fault detection. These collaborations extend the utility of Astrobee beyond its operational role, making it a shared research asset for academic, government, and industry investigators in exploring free-flyer technologies.

Some of Astrobee's guest science topics include:

- hardware manipulation payloads
- optimal pathplanning algorithms
- machine learning in microgravity
- anomaly detection and station upkeep

B. *Manipulation*

Astrobee's manipulation capabilities extend its role beyond inspection to physical interaction with the environment. Astrobee's 3-DOF perching arm payload allows for grasping and stabilizing of itself against ISS handrails and other fixed structures on the JEM. By doing so, Astrobee can conserve propellant during prolonged tasks, enabling operations that require sustained positioning or external force application. The perching arm also facilitates microgravity operations involving light-duty manipulation, such as toggling switches, repositioning small objects, transporting ISS cargo transfer bag (CTB) or interfacing with ISS hardware, significantly expanding the Astrobee's versatility within confined intra-vehicular environments.

Beyond the perching arm, Astrobee has served as a host for several experimental manipulation payloads. One such effort is Stanford's gecko-adhesion gripper project, which tested bio-inspired adhesive pads modeled after gecko feet in microgravity. These adhesion pads enable Astrobee to attach to smooth surfaces without hooks or magnetic mounts, opening new possibilities for stable positioning in areas without the need of ISS handrails.

More recently, the Responsive Engaging Arms for Captive Care and Handling (REACCH) payload introduced a soft robotic end-effector designed for expressive interaction and dexterous manipulation tasks. Such tasks including entire grasping of large transfer boxes as seen in Fig. 8e. Other experimental payloads have explored the development of optimized underactuated gripper payloads as seen in Fig. 8d. which is ideal for the temperature dissipation and fire safety on ISS. This modular hardware interface positions Astrobee as a versatile testbed for robotic free-flying manipulation payloads that could support future crew assistance and autonomous servicing missions on-orbit.

C. *Astrobee Zero Robotics*

Astrobee continued the SPHERES tradition of hosting MIT's annual ZR competition in 2019. With upgraded payloads and on-board technologies for vision, processing, and

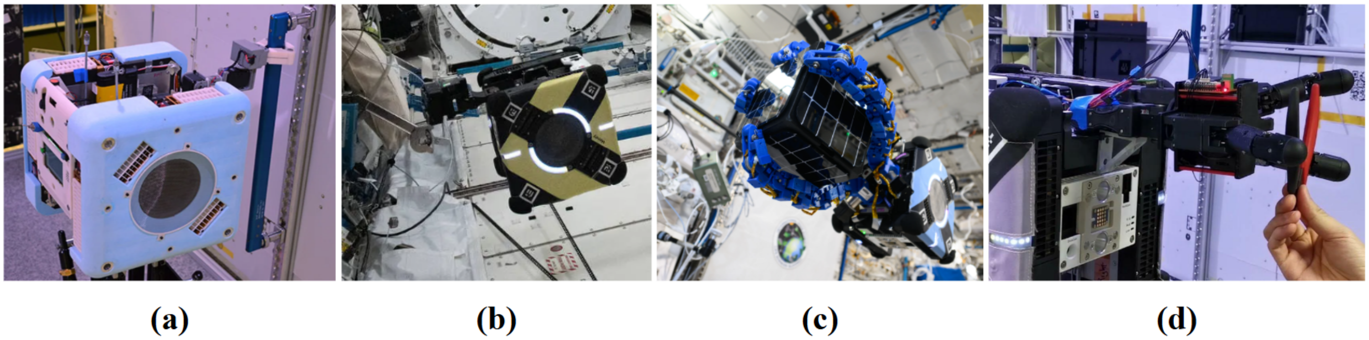


Fig. 8. 8a: Astrobee's 3-DOF perching arm payload (photo credits: NASA), 8b: Gecko-adhesion gripper payload (photo credits: Stanford ASL and NASA) 8c: Responsive Engaging Arms for Captive Care and Handling, or REACCH payload (photo credits: Kall Morris Inc.), 8d: Three-finger Astrobee gripper (photo credits: Columbia ROAM Lab)

hardware integration, novel challenges and more STEM outreach was enabled by Astrobee. This collaborative effort between MIT, NASA, ISS National Lab, and industry partners such as the Aerospace Co. reached thousands of middle and high school students around the world with new challenges in perseption and microgravity-enabled free-flier games.

D. Integrated System for Autonomous and Adaptive Caretaking

Astrobee have become instrumental in advancing free-flying autonomous inspection and routine spacecraft upkeep through NASA's Integrated System for Autonomous and Adaptive Caretaking (ISAAC) Project. ISAAC was designed to operate independently of crew-assigned schedules, and conduct visual inspections of the station's infrastructure using Astrobee's onboard suite of cameras and sensors. Astrobee's free-flying mobility allows it to maneuver into tight or difficult-to-reach areas, making it ideal for capturing detailed visual data of cabin interiors, payload racks, and other experimental modules in the JEM. This repeated monitoring could reduce crew workload and ensures that routine system health management can be performed consistently and without crew involvement. This could be especially useful for future space stations where there may be periods of uncrewed time.

Astrobee's autonomy enables the free-flier to document various configurations, monitor ISS experiment racks, and identify potential faults such as foreign object debris (FOD) or hardware misalignment. Importantly, Astrobee can return to specific inspection waypoints, allowing for time-lapse comparison and condition tracking over weeks or months, thereby supporting early detection of system degradation or various anomalous behaviors. ISAAC also integrated advanced computer vision (CV) and machine learning (ML) algorithms with Astrobee's computational framework interface to enable real-time analysis of visual inspection data. This could be done onboard and via edge computing, allowing for Astrobee to autonomously detect anomalies such as mechanical wear, sensor faults, or displacement of hardware components. This transforms Astrobee from a mobile camera platform into an intelligent station caretaker, capable of monitoring spacecraft health continuously. Through ISAAC and similar efforts, Astrobee enables a foundation where future free-fliers could autonomously maintain and safely assure station system health during long-duration and uncrewed spaceflight missions.

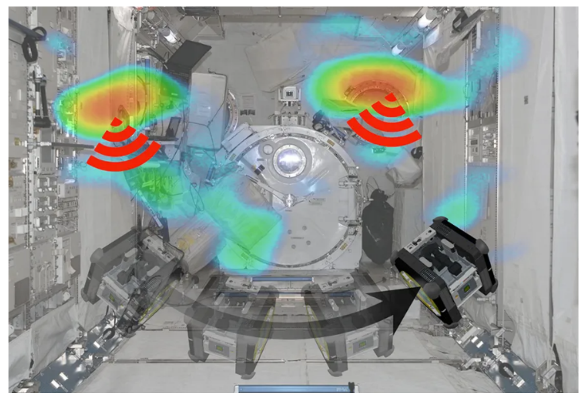


Fig. 9. Conceptual image of Astrobee scanning a uncrewed space station. (credits: NASA)

VI. Int-Ball2

Int-Ball2 is JAXA's second-generation intra-vehicular free-flying robot following the deployment of Int-Ball. Designed to enhance autonomous visual documentation capabilities, Int-Ball2 incorporates key hardware and software improvements based on operational feedback from lessons learned through Int-Ball. These upgrades include improved propulsion control for more stable flight, higher-resolution imaging sensors, and more robust communication links to enable seamless interaction with ground control. Int-Ball2 continued to operate within the JEM, focusing on the same ConOps of Int-Ball for reducing astronaut time spent on routine photography and inspection tasks. Fig. 10a and b below show Int-Ball one (left) and Int-Ball2 (right) as a comparison of the two free-flying robots.

Beyond incremental technical enhancements, Int-Ball2 represents a shift toward greater operational autonomy and reliability in intra-vehicular free-fliers for vision-based IVA. Its development reinforces JAXA's long-term vision of intelligent robotic assistants in space in capabilities of repeatedly monitoring onboard system health, support maintenance activities, and reduce crew workload through assistive imagery. Int-Ball2 serves as both an evolutionary step in robotic utility aboard the ISS and a testbed for future vision-based low-cost intra-vehicular free-fliers.

VII. Discussion

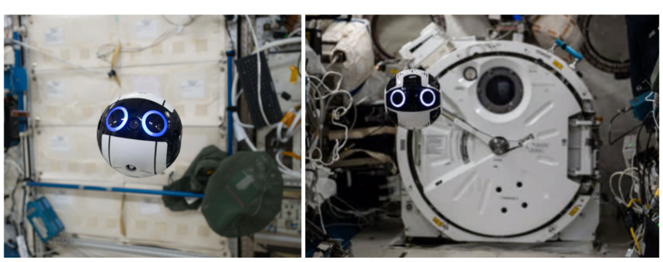
The evolution of free-flying robots aboard the International Space Station reflects a steady progression in autonomy, sensing, and onboard intelligence. The SPHERES program laid the foundational groundwork, demonstrating core mobility, formation flying, and control algorithms for autonomous robots in microgravity. However, SPHERES was limited in power, computation, and sensing capabilities, relying heavily on ground-based processing and pre-programmed tasks. Int-Ball, developed by JAXA, advanced this baseline by integrating real-time video streaming, enabling remote monitoring and crew support. It emphasized visual communication and telepresence, but lacked autonomy and physical interaction capabilities.

Astrobee represented a major leap forward, incorporating high-resolution vision, autonomous navigation, robust onboard computation, and modular payload support. Its perching arm, multiple vision systems, and compatibility with experimental hardware allowed Astrobee to function as both a science platform and an operational assistant. The robot's ability to autonomously execute inspection routines and interface with external software like ISAAC marked a shift toward intelligent spacecraft caretaking. Meanwhile, CIMON and CIMON-2 introduced AI-driven interaction through natural language processing and contextual understanding, emphasizing social robotics and crew companionship in addition to functional support. These advancements collectively pushed the state-of-the-art in mobile, intelligent, and interactive space systems.

A. Opportunities

Despite these developments, significant capability gaps remain. Current free-fliers are not yet integrated deeply into daily crew workflows or real-time station operations, and their roles are often limited to short-duration tasks or demonstrations. Gaps in persistent station upkeep, dynamic anomaly response, and adaptive tasking remain only partially addressed. For instance, while Astrobee supports inspection, it is not yet capable of autonomous maintenance or active repairs. Similarly, systems like CIMON offer conversational interfaces but lack the embodiment or situational awareness for interactive collaboration during complex crew procedures. Teleoperation latency, especially for Earth-based commanding, still constrains responsiveness, and robust methods for human-robot teaming under time-pressured conditions remain underdeveloped.

To fully realize the potential of intravehicular free-flying robots, future research must bridge these gaps. This includes refining autonomy to handle unscripted tasks, improving perception systems for contextual understanding, and expanding manipulation to handle real maintenance operations. It also involves rethinking human-robot interaction to move beyond passive interfaces toward collaborative behaviors and trust-building with crew. Closing these technical and operational gaps will not only enhance the utility of free-fliers on the ISS but will be essential for long-duration missions to the Moon and Mars, where robotic systems must function as proactive teammates in dynamic, crewed environments.



(a) **(b)**

Fig. 10. Comparison between Int-Ball and Int-Ball2 on the ISS 10a: Image of Int-Ball free-flying aboard the JEM 10b: Int-Ball2 free-flying aboard the JEM

VIII. Conclusion

Intra-vehicular free-flying robots have evolved from ISS testbed platforms into multi-purpose modular agents capable of supporting a range of IVA including spaceflight operations, microgravity guest science, and crew interaction. While platforms like SPHERES, Int-Ball, Astrobee, and CIMON have demonstrated key advancements in autonomy, inspection, and human-robot collaboration, many of their originally intended capabilities remain only partially realized, leaving open challenges and opportunities for future free-fliers. Free-fliers established by these five robots provide a baseline for future innovation in free-flying technology. As future space stations extend beyond low-Earth orbit, the continued development and refinement of intra-vehicular free-fliers will be essential to enabling persistent autonomy, intelligent spacecraft care taking, and adaptive support systems, and reduction of crew workload and enhance mission resilience.

Acknowledgments

The authors would like to thank the support of the Intelligent Robotics Group at NASA Ames Research Center, namely Jose Benavides, Matthew Deans, and Uland Wang. Furthermore, the authors would like to thank the support of the Astrobee Facilities Team, namely Andres Mora, Aric Katterhagen, and Jonathan Barlow.

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