ADVANCES, OPPORTUNITIES AND CHALLENGES IN REMOTE SAMPLE HANDLING FOR ASTROMATERIAL CURATION AND RESEARCH. J. Emmanuel Torres[1], Kimberly Allums[2], Salvador Martinez[1], Neftali Hernandez[3], Gabriel Lugo[4]; [1]Amentum, JETS II, NASA Johnson Space Center, Houston, [2]HX5, LLC, JETS II, NASA Johnson Space Center, Houston, [3]GeoControl Systems, Inc., JETS II, NASA Johnson Space Center, Houston, [4]MRI Technologies, JETS II, NASA Johnson Space Center, Houston; Email: jesus.e.torresgarcia@nasa.gov

Introduction: Astromaterials provide crucial insights into the history and formation of the solar system. Within the efforts to develop new curation tools and techniques for astromaterials at NASA's Johnson Space Center, manually and electronically controlled micromanipulation systems show potential. Robotic arms for micromanipulation present a promising solution to enhance the curation process, offering precision and efficiency. [1]

Astromaterials Curation Robotics has identified potential opportunities, and challenges associated with the use of controlled micromanipulation robotic arms in the curation of astromaterials, particularly in controlled environments such as glove boxes, highlighting how robotic arms can improve efficiency and safety in sample handling while addressing specific challenges that arise in this new and specialized field.

Advances in Robotics: NASA's Johnson Space Center (JSC) is at the forefront of developing robotic tools for astromaterials curation. The current methodologies often rely on manual manipulation, which can lead to operator fatigue and contamination risks. Recent efforts focus on integrating robotic arms that can perform micromanipulation tasks with precision.

The introduction of the Meca500 arm, with its 5 µm repeatability, suggests a substantial advancement in robotic precision. The Meca500 is a desktop-sized, six-degrees-of-freedom industrial robotic arm with a range of motion reaching 260 mm, allowing for greater reach capability than currently deployed systems and providing suitability for a variety of micromanipulation operations. Although the manufacturer's specifications state a 5 µm repeatability capability, testing indicates it is capable of 1 µm increments of motion in the Cartesian motion format. While the Meca500 is proprietary, it employs TCP/IP protocols and standard Ethernet connectivity, with RoboDK implementation, which allows user operation in real time. [2] This capacity of external control and custom development, provides an avenue to develop custom control methods. Using the Python programming language, various forms of control input (including a custom graphical user interface) have been tested.

The accuracy of motion through real time control has been demonstrated in past studies, subsequently, a variety of end effectors for the robotic arm were developed. A stylus mount, which permitted a pen to be held in the arm and controlled via an interface, allowed testing of the motion output of the controls, as well as identifying and correcting a deviation in the vertical axis when moving in the x-y plane [2].

Following end effectors consisted of different sets of jaws that connected to a Schunk MEGP 25 miniature electrical parallel gripper. These sets of jaws made it possible to collect glass beads of sizes between 0.5 and 2 mm and to determine and limit the force applied to grip the object of interest.[3]

One of the jaws featured a dedicated groove designed to securely clamp a vice. The vice held a glass rod which was then used to manipulate magnetic grains of size between 10 and 30 um. As an intermediate component between the above designs, a set of holders was designed to hold and operate tweezers using the MEGP 25 gripper. [3]

The latest manipulator prototype is a mount to directly hold a pin vice allowing for more stability in manipulating small particles than the grooved jaw. All these are first stage prototypes.

Opportunities in Implementation: Future possible applications with robotic arms include tasks such as initial sample viewing, storage, retrieval, and sample preparation, which encompass polishing, inspection, cutting, and grinding. Further applications, could include, to conduct non-destructive analyses, such as X-ray diffraction and UV-Vis spectroscopy, further enhancing its utility [4]. The integration of robotic arms into cryogenic environments also presents significant opportunities for advancing astromaterial curation. Cryogenic operations are essential to preserve the pristine state of volatile-rich extraterrestrial samples, such as those from comets, asteroids, planetary, among others, which can degrade at higher temperatures. Robotic arms, with their precision and ability to operate under controlled conditions, offer a promising solution to manipulate such delicate materials while reducing the risk of contamination. Robotic systems developed or optimized specifically for cryogenic environments can enable tasks such as sample extraction, storage, and analysis in ultracold environments. Furthermore, the use of automated or remote-controlled robotic systems minimizes the need for direct human intervention, reducing the risk of compromising the sample while maintaining strict environmental parameters. The employment or development of intuitive control

interfaces, such as those with haptic feedback or telepresence capabilities, would further enhance the dexterity required for these operations, ensuring that cryogenic preservation meets the rigorous demands of next-generation planetary science missions. These advancements could transform cryogenic curation from a labor-intensive process to a scalable and precise methodology, paving the way for handling even more complex sample types in the future.

Challenges in Implementation: Despite the promising developments in robotic systems, several challenges remain. Current robotic arms often have limitations regarding their degrees of freedom, which restricts their ability to perform tasks that require nuanced movements, such as scooping and rotating particles. Existing three-axis micromanipulators have been successful in certain applications but are inadequate for more complex manipulations required in astromaterial handling. Additionally, the transition from manual to robotic operations requires the design of intuitive control systems that can replicate the dexterity of human operators.

The integration of high-resolution cameras and haptic control technologies is being explored to enhance robotic capabilities. This could allow curators to operate robotic systems remotely, mimicking hand movements to manipulate samples with a similar level of dexterity as they would in a traditional setting. However, the proprietary nature of some robotic systems present challenges in customization and optimization, which may hinder their widespread adoption in curatorial facilities.

Robotic systems for cryogenic curation present several critical challenges. One of the main issues is the need for cryogenically compatible materials and components. Many robotic components, such as motors, joints, and sensors, are designed for ambient or moderate temperatures, and their performance can be significantly degraded at cryogenic temperatures due to material embrittlement, thermal shrinkage, or lubricant failure. Ensuring that components operate reliably in extreme cold conditions requires extensive testing of materials and the integration of specialized cryogenic components. Insulation and thermal management also pose significant challenges, as robotic arms must operate in ultracold environments and prevent heat transfer that could compromise the sample or surrounding environment. Another issue is condensation and ice formation on robotic components, which can impair functionality and increase the risk of contamination. In addition, the design and implementation of control systems for cryogenic operations must account for the slower response times and altered dynamics of materials at low temperatures. Addressing these challenges is essential to ensure that robotic systems can safely and reliably manipulate sensitive astromaterials under cryogenic conditions.

Future Research Directions: Ongoing research aims to refine robotic designs and develop new end effectors suited for specific tasks in astromaterial conservation, as well as control methods. For example, 3D printed manipulators and custom grippers have been tested to improve handling accuracy and reduce the risk of sample contamination.

The exploratory of haptic feedback devices may provide the necessary interface to control these robotic systems more intuitively, enhancing the operational experience for curators. As the technology evolves, the potential for robotics arms to significantly improve astromaterial curation processes becomes increasingly tangible, paving the way from more efficient and contamination free analysis of extraterrestrial materials.

Another end goal is to create a robotic system capable of performing delicate manipulations in environments that may be nitrogen or cryogenically cooled, thus meeting the stringent requirements for handling sensitive extraterrestrial samples. The focus on this area will be the exploration of innovative insulation techniques and thermal management systems to mitigate heat transfer, ensuring the stability of both the robotic systems and the cryogenic samples. Development of modular robotic designs that allow for easy customization and replacement of components to adapt to diverse cryogenic environments and tasks should be pursued. Furthermore, interdisciplinary collaborations could drive the development of hybrid systems combining cryogenics with other environmental conditions, to expand the range of applications. These efforts will not only enhance the feasibility of robotic cryogenic operations but also pave the way for their deployment in future space missions and astromaterial curation facilities.

References: [1] Allen, C., Alton, J., Lofgren, G., Righter, K., Zeigler, R., & Zolensky, M. (2013, July 16). Curating nasa's extraterrestrial samples. Eos, Transactions, American Geophysical Union, 94(29), 253–260. [2] Cowden, T. R., Snead, C. J., Jang, J. H., & McCubbin, F. M. (2019). Meca500 Robotic Arm Developments Towards Astromaterials Curation Applications.
https://ntrs.nasa.gov/api/citations/20190027196/downloads/20190027196.pdf. [3] Cowden, T.R., Snead, C.J., Jan J.H, and McCubbin, F, M. (2020). Robotic Arm Developments Towards Astromaterials Curation Applications. 51st Lunar and Planetary Science Conference. [4] Osinski, G.R., Banerjee, Brown, P. Fleming, R., Ghafoor, N., McIsaac, K., Naish, M., Ower, C., Patel, R., and Southam, G. (2011). Robotic Sample Curation, Handling, Manipulation, and Anslysis: The Future Of Sample Return Facilities?