Robotic Arms: A Critical Element of any Mars Landed Mission. J. A. Middleton\textsuperscript{1}, C. S. Sallaberger\textsuperscript{2} and T. J. Reedman\textsuperscript{3}, \textsuperscript{1}Vice-President, Strategic Development, MD Space and Advanced Robotics, 9445 Airport Road, Brampton, Ontario, Canada L6S 4J3, jmiddlet@mdrobotics.ca, \textsuperscript{2}Director, Space Exploration, MD Space and Advanced Robotics, 9445 Airport Road, Brampton, Ontario, Canada L6S 4J3, csallabe@mdrobotics.ca, \textsuperscript{3}Chief Engineer, Advanced Systems Group, MD Space and Advanced Robotics, 9445 Airport Road, Brampton, Ontario, Canada L6S 4J3, treedman@mdrobotics.ca.

Introduction: Landed exploration of Mars requires robust robotic systems capable of satisfying the demands of multiple scientific users. Whether the landed system is a stationary lander or a mobile rover, a robotic arm is an essential element of an exploration system that satisfies scientific needs while providing a method of dealing with unexpected contingencies.

The basic purpose of any landed system is to explore and examine the surface and sub-surface of the planet in question, perhaps in conjunction with technology demonstration elements. To this end the basic needs for exploration are the deployment and retrieval of experiments to and from the surface, the acquisition of surface and sub-surface samples for analysis, and the imaging of the local environment.

A robotic arm satisfies these requirements in a resource efficient manner and also adds an element of robustness to the system.

Mission Architecture: A typical landed exploration system has as its central element a science platform (either static or mobile) capable of supporting a wide range of scientific payloads to examine and determine the state of the planet’s surface. The highest level needs for such a system are to:

1. Deploy experiments and instruments of varying sizes to the planet’s surface
2. Acquire surface and sub-surface samples and provide them to science instruments for local analysis.
3. Acquire surface and sub-surface samples and transfer to the sample return vehicle (for sample return missions)
4. Provide imagery of the local terrain

An overarching requirement not listed above is the need for a robust system that minimizes the risk of mission failure.

Capabilities. These system needs can be synthesized into the following necessary system capabilities:

1. Handling of multiple payloads varying in size from soil samples on the order of many grams to a rover on the order of many kilograms.
2. Provision of power and data connections to payloads.
3. Dexterity in payload handling to ensure accurate placement and orientation of payloads on either the science deck or the planet surface.
4. Force application sufficient to react both digging and drilling loads
5. Camera support to allow varied imaging of the local workspace.

Generic System Architecture: A robotic arm can used as the basis for a generic system architecture that effectively provides these capabilities, for missions ranging in size from the Mars Surveyor class landed systems to small Beagle II type landers.

Such a robotic arm would require between 4 and 6 degrees of freedom depending on the specific mission needs. Mass, power and load capacity would be commensurate with the landed system size. The end effector would be capable of handling and servicing many different payloads, varying from digging tools to science instruments. To deal with the limited communications available, the system would be semi-autonomous and capable of some self-diagnosis.

An Illustrative Application: This approach was recently the subject of a feasibility study conducted by MD Robotics, where a systems engineering approach to the mission architecture derived a robotic arm as a solution to the needs of the Mars Sample Return Missions.

System Description. The robotic arm was a 4 degree of freedom pitch plane manipulator with a mass of 7 kg including processing electronics. Power consumed varied between 10 and 20 watts depending on the operating mode and the task being performed. The manipulator had a maximum reach of 2.8m allowing a 2.2m radius surface work area. The manipulator tip was equipped with a multi-purpose end effector capable of handling payloads ranging from an 8 kg sampling drill to rover samples. In order to avoid duplication of existing lander functionality, for the Mars 2003 mission a camera was not included in the arm manifest; however, structural and electrical scarring for a camera was provided.

The tasks envisioned for the arm included experiment deployment and sample acquisition and transfer. The needs of the scientific community were met through the use of a multi-purpose end effector that
allowed the handling of diverse payloads. Power and data lines routed along the arm were connected to the current payload via an umbilical mechanism to allow experiment operation, control and data acquisition by the landed system central processor.

In this proposed architecture, valuable mission robustness was achieved simply by having a flexible, reconfigurable robot in-situ. Should a problem have arisen in the deployment of another lander system the robot arm could be used to investigate the anomaly, providing the earthbound system operators with insight into the situation. If force were required to assist in deployment of a stuck system such as an antenna, the arm could have provided the required impetus.

**Risk Management:** The utility of a robotic arm in managing mission risk is perhaps best illustrated by considering its potential application in the original Mars sample return missions. The Athena rover was seen as the primary sample retrieval chain. It was deployed by driving down ramps extended from the Lander deck and had to re-ascent the ramps to transfer its samples to the ascent vehicle. The secondary sample retrieval chain was a coring drill, deployed using a simple positioning mechanism.

Using a robotic arm on this mission to deploy the coring drill for its sample acquisition activities created some useful risk management possibilities. For instance, while the arm’s primary task was to support the secondary sample retrieval by deploying the coring drill, it could also be used to backstop the primary sample retrieval chain. If the rover ramps became stuck during deployment, the arm could be used to apply assistive force. If the rover required assistance during deployment, the arm could once again apply assistive force. If the rover had difficulty ascending the ramps to transfer its sample to the ascent vehicle, the arm could be used to acquire the samples from the rover on the planet’s surface and then deposit them in the ascent vehicle.

In this example application, the robotic arm effectively mitigates mission risk while providing basic functionality for the core mission objective, namely sample retrieval. Other possible contingency activities include assisting in antenna deployment and the cleaning of dust covered optical surfaces such as solar arrays.

**Conclusions:** A robotic arm should be part of the infrastructure of any multi-purpose landed Mars mission as a method of efficiently deploying and supporting instruments, performing sample collection and sample distribution, while also significantly enhancing mission robustness through its capabilities for contingency operations.