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Are We There Yet? ... Developing In Situ Fabrication and Repair (ISFR) Technologies to Explore and Live on the Moon and Mars

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NASA's human exploration initiative poses great opportunity and great risk for manned missions to the Moon and Mars. Engineers and Scientists at the Marshall Space Flight Center (MSFC) are evaluating current technologies for in situ resource-based exploration fabrication and repair applications. Several technologies to be addressed in this paper have technology readiness levels (TRLs) that are currently mature enough to pursue for exploration purposes. However, many technologies offer promising applications but these must be pulled along by the demands and applications of this great initiative. The In Situ Fabrication and Repair (ISFR) Element will supply and push state of the art technologies for applications such as habitat structure development, in situ resource utilization for tool and part fabrication, and repair and replacement of common life support elements, as well as non-destructive evaluation. This paper will address current rapid prototyping technologies, their ISFR applications and near term advancements. We will discuss the anticipated need to utilize in situ resources to produce replacement parts and fabricate repairs to vehicles, habitats, life support and quality of life elements. Many ISFR technology developments will incorporate automated deployment and robotic construction and fabrication techniques. The current state of the art for these applications is fascinating, but the future is out of this world.

I. Introduction

The In Situ Fabrication and Repair (ISFR) Element originated out of the Human Exploration Initiative as an essential task to facilitate the goals of the initiative. The ISFR system has the mission to provide a necessary function of fabrication and repair of equipment and materials at the location where the equipment is operating, i.e., in situ. The scope of this activity includes all mechanical, electrical, and some biological components and assemblies to progress technologically in a phased approach to meet the increasing scope of the Exploration

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Initiative. The scope of this effort includes the development of supporting fabrication, repair and habitat structures technologies for manned missions that maximize the use of in-situ resources to address the following agency topics:

1. Bioastronautics Critical Path Roadmap (BCPR) (Ref. 1) risks
2. Strategic Technical Challenges defined in Human &Robotics Technology (H&RT) Formulation Plan (Ref. 2)

ISFR enables evolution of human space exploration by:

- Reducing downtime of failed components thereby **decreasing risk to crew and system functionality and enhancing mission safety**
- Reducing crew exposure to environment by providing autonomous non-destructive evaluation technologies that are capable of identifying and confirming a failure and then validating the repair method was successful
- Providing habitat manufacturing and assembly technologies that incorporate in-situ resources and produce autonomous, affordable, pre-positioned habitat environments with radiation shielding features and protection from micrometeorites and exhaust plumes
- **Reducing upmass/upvolume resource requirements** for supply of spares and materials from Earth by utilizing in-situ resources
- Providing just-in-time fabrication of parts and tools to meet maintenance requirements of system failures via closed loop quality controlled solid freeform fabrication technologies, thereby **reducing spare parts inventory**
- Providing just-in-time repair capability via soldering, patching, self-healing materials, or adhesives

To perform this function, the ISFR element will support a variety of equipment solutions, including handheld tools, portable machines, stationary or shop level machines, and mobile systems with capabilities for performing the mission functions. At the onset of deployment, the capabilities will be in line with small volume, small resource limitations of early flights, such as handheld tools and small parts makers or portable units. As the program reaches its full-scale deployment phase, equipment capabilities such as a mobile parts hospital Fabrication and Repair Module (FARM) are planned to support the comprehensive and large-scale needs of Mars habitation. The primary objectives of the ISFR are:

1. Provide fabrication and repair services commensurate with the needs of the Flight, Moon, and Mars mission operational plans.
2. Provide fabrication and repair capability for unforeseen tools and parts.
3. Provide habitat construction and repair/maintenance capability.
4. Provide inspection, testing, and troubleshooting service as an offshoot of fabrication inspection and test.

The ISFR Element is composed of the following subelements:

1. Fabrication Technologies Subelement: Includes parts and tools fabricated using additive, subtractive, conventional and hybrid technologies. Metals, nonmetals (including biological), and composites.
2. Repair and NDE Technologies Subelement: Includes mobile, shop, portable, and handheld equipment. Metals, nonmetals (including biological), and composites.
3. Habitat Structures Subelement: Structural element and radiation shielding element fabrication and repair capabilities.

II. Fabrication Technologies Subelement Overview

The current Fabrication Technologies scope covers additive, subtractive, conventional, and hybrid manufacturing processes. A detailed trade study has been issued relative to these technologies, which selects possible candidates for continued evaluation as spaceflight fabrication systems.

Additive processes typically allow elimination of intermediate tooling steps, thus requiring fewer volume resources for processing equipment. For instance, conventional hot forming by casting methods or forging requires mold tooling to be created from part patterns prior to manufacture of the actual parts. In cases where low part counts are required, additive processes typically offer lower resource requirements. However, large part count scenarios may result in favorable advantages for conventional machining or fabrication technologies adapted for space missions.

The Trade Study activity served to identify core technologies that will close gaps in current manufacturing technologies for space missions. They were identified by engineering judgment of factors such as fabrication speed limitations, geometric accuracy and tolerance assessment, and resource savings that might be realized by enhancement of current state of the art processing methods. Page limitations make it impractical to describe the large number of conventional manufacturing or solid freeform techniques that were evaluated, but the reader is urged to visit the Worldwide Guide to Rapid Prototyping (http://home.att.net/~castleisland/home.htm), and review their tutorial for solid freeform processes and other rapid prototyping technologies. Specific manufacturers' web pages may also be searched for process information not included there.

Solid Freeform Fabrication (SFF) is an essential technology that enables fabrication of any three-dimensional object directly from a computer data file, e.g. CAD data. KC-135 testing has been successfully completed by MSFC. Two technology demonstrations on ISS using various plastics, metals, ceramics, electronics and composites to fabricate parts will lead to a production unit for the moon. MSFC is teaming with LaRC, JSC, and GRC to achieve TRL of 6 for these technologies within 5 years.

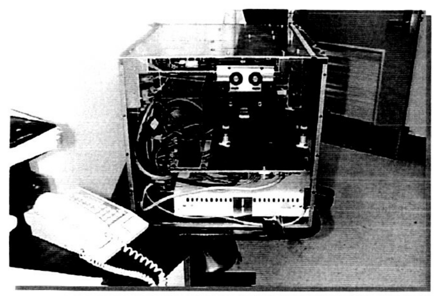

Figure 1. NASA/MSFC Stratasys SFF Apparatus Flown on the KC-135 Aircraft

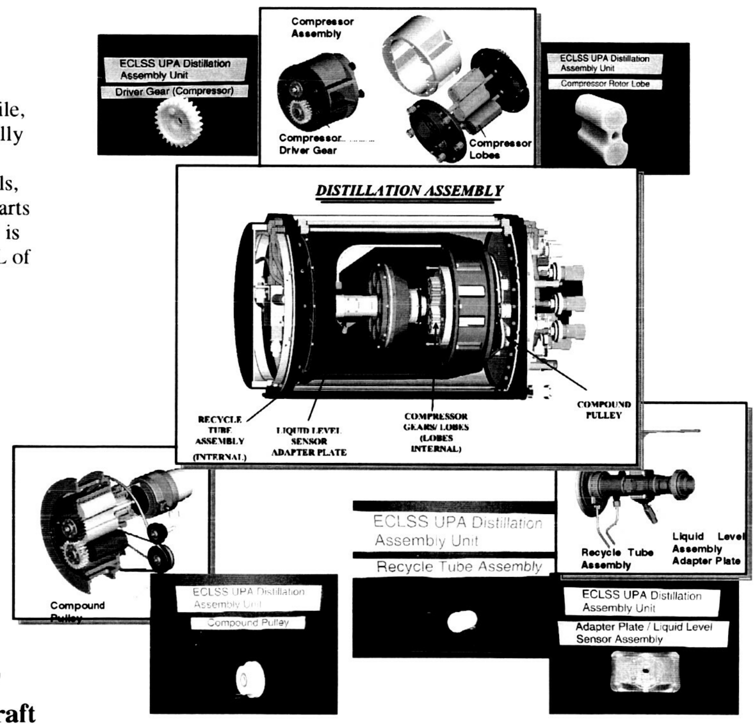

Figure 2. ISS ECLSS Urine Processor Distillation Assembly Parts Produced by SFF

The type of feedstock these processes utilized was important in the evaluation process. Management and usage of bulk powders, sprayed powders, wires, filaments, tapes, stock shapes (plate, channels, ells, tees, etc.), and liquids, were evaluated for microgravity and hypo-gravity applications. The possibility of producing these feedstocks from in situ regolith or a recycle stream was also evaluated.

Most of these processes (as ground based equipment) are heavy and voluminous, and require relatively large amounts of alternating current power. Development of units for spaceflight must be designed for weight and volume reduction and utilization of alternative power sources. The flight systems must be ruggedized to support launch and landing while providing long mean time between failures (MTBF).

III. Repair and NDE Technologies Subelement Overview

A wide range of systems is being analyzed for repair potential by the Repair & NDE Technologies sub-element within the ISFR team. These systems and the capabilities involved in their repair, as well as the underlying technologies, are being analyzed through a series of comprehensive trade studies to evaluate the potentials for advancement and the ability to fulfill expected needs of Exploration Systems infrastructure.

Repair of electrical components (through such technologies as soldering), permanent full-strength metal repairs (including numerous welding techniques), composites repairs (including bonding repairs), biological repairs (including using tissue grown in situ), multi-material repairs (with one- and two-part adhesives, amalgams and tapes), self-healing capabilities (including self-healing wire insulation) and the underlying technologies of each are being analyzed.

Initial analyses and studies are intended to determine the capabilities that are the most valuable for the likely systems to be encountered in long duration missions. One step in this is the completion of a series of analyses of historical parts failures in previous space flight and in other relevant systems. These results can be imperfectly extrapolated to likely systems and classes of parts for future space missions. This is used as one input to determining what repair capabilities are most needed. For example, one area of high historical failure rates has been among electrical systems and electrical components. To perform repairs on electrical components below the Orbital Replacement Unit (ORU) level, it is expected that soldering will have to be performed in flight and on the surface of the Moon and Mars. Early experimentation aboard the International Space Station (ISS) has demonstrated unexpected results and odd behaviors of liquid solder in microgravity. Theoretical calculations indicate some expected difficulties with the quality of soldered joints produced in microgravity – the results of the In-Space Soldering Investigation (ISSI) will allow these effects to be quantified and the areas for further refinement and advancement to be more fully defined. Test coupons soldered aboard the ISS will be brought to Earth upon the Shuttle's return to flight.

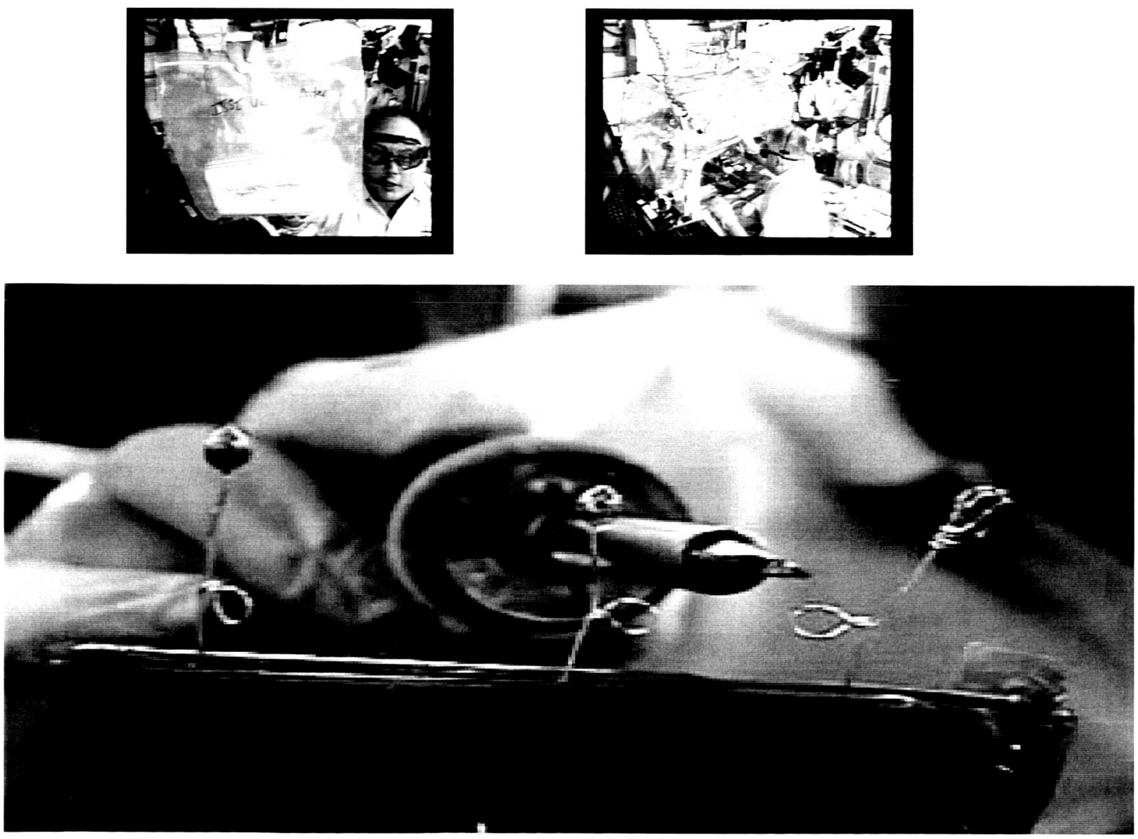

Figure 3. Mike Fincke Conducting the ISSI Experiment in the ISS Workbench 10 July 2004

Nondestructive evaluation (NDE) is a set of necessary support technologies for the in situ fabrication and repair of parts and systems, as well as a set of enabling technologies for other capabilities that are necessary for long-duration missions beyond the vicinity of Earth. The fabrication of parts and tools performed in situ requires the validation of the fabrication techniques utilized. The ultimate goal is a closed-loop system with NDE performed at each step (layer) of fabrication, and control systems designed to utilize the feedback received to adjust the building characteristics and optimize the overall fabrication. As a preliminary step to that ultimate goal, the constituents of the feedstock of fabrication systems must be analyzed, if it comes from resources obtained in situ, as opposed to feedstock brought along from Earth. Utilization of resources obtained from in situ sources is necessary for the maximum savings in upmass; if all the feedstock is brought along from Earth, the mass of spare parts saved would be offset by the mass of the feedstock and the necessary fabrication equipment. Another preliminary step is the analysis of a part or tool post-production, to verify the quality of the part produced, but this does not allow for corrections to be made during production. Errors made in fabrication and detected only after completion would necessitate the scrapping of the entire part.

Repair in situ will also require validation of work performed, requiring the use of NDE techniques. Depending on the type of system repaired, and the repair performed, the specific NDE technique (technology) employed will vary. Therefore, to cover the widest range possible of applications, a suite of NDE tools must be prepared, and thus a range of technologies must be advanced to the point where their application in a space environment is possible.

Structures and critical components (including habitats) in vehicular and Moon- and Mars-based systems will require substantial preventative maintenance inspections and troubleshooting for continued safe operation. The technologies needed to develop these capabilities also require maturation for deployment. The ultimate goal is the incorporation of robotic and autonomous systems internal to employed structures that will allow immediate feedback and that will initiate corrective measures for detected off-nominal conditions.

The Repair & NDE Technologies sub-element within the ISFR team is performing evaluation of NDE capabilities and technologies through a series of trade studies, designed to arrive at the optimum suite of technologies for advancement. Among the technology areas under consideration are thermal imaging techniques, laser techniques, electronics applications, x-ray techniques, acoustic, electromagnetic and chemical methods. These will all be analyzed for their range of potential uses and the advantages of each, and specific technologies will be selected for maturation as necessary to meet ISFR goals.

IV. Habitat Structures Subelement Overview

The Habitat Structures subelement will provide a means of protecting personnel, other systems and itself within the system of the habitat from the damaging effects of external environments on Moon and Mars. The Habitat Structures subelement will use available materials as provided by a logistics support function which will include limited new and primarily in situ materials for structure construction. Habitat Structures will prioritize protection of personnel, equipment, and other systems in that order.

The ISFR Element at MSFC is primarily focusing on the development of Class III habitats. Class III habitats are those habitats which may be built on Earth, but incorporate in situ materials on the surface, or the primary structure may use in situ construction. As part of this task, a number of in situ material-based construction technologies have been identified, and have been subjected to a rigorous trade study evaluation with respect to exploration and other performance criteria by the Habitat Structures group within NASA/Marshall Space Flight Center's ISFR team. Results of this study have been published in a separate paper, titled In Situ Resource-Based Lunar and Martian Habitat Structures Development at NASA/MSFC (Ref. 3). In addition, details on the Contour Crafting technology, which was evaluated as part of the trade study, are documented in a paper titled: Lunar Contour Crafting – A Novel Technique for ISRU-Based Habitat Development (Ref. 4).

V. Summary

The ISFR trade study roadmaps include a fabrication, assembly and repair module (FARM, Figure 4), which could contain many of the elements of a modern machine shop with the addition of SFF machines to augment the functionality. Also included would be electronic repair and test equipment, nondestructive evaluation equipment, and life support for a shirtsleeve working environment. This complex system would require a robust landing craft and is well suited for long duration planet exploration bases. This fabrication module could become part of the later exploration spirals as space designed fabricators evolve over the next 10 years.

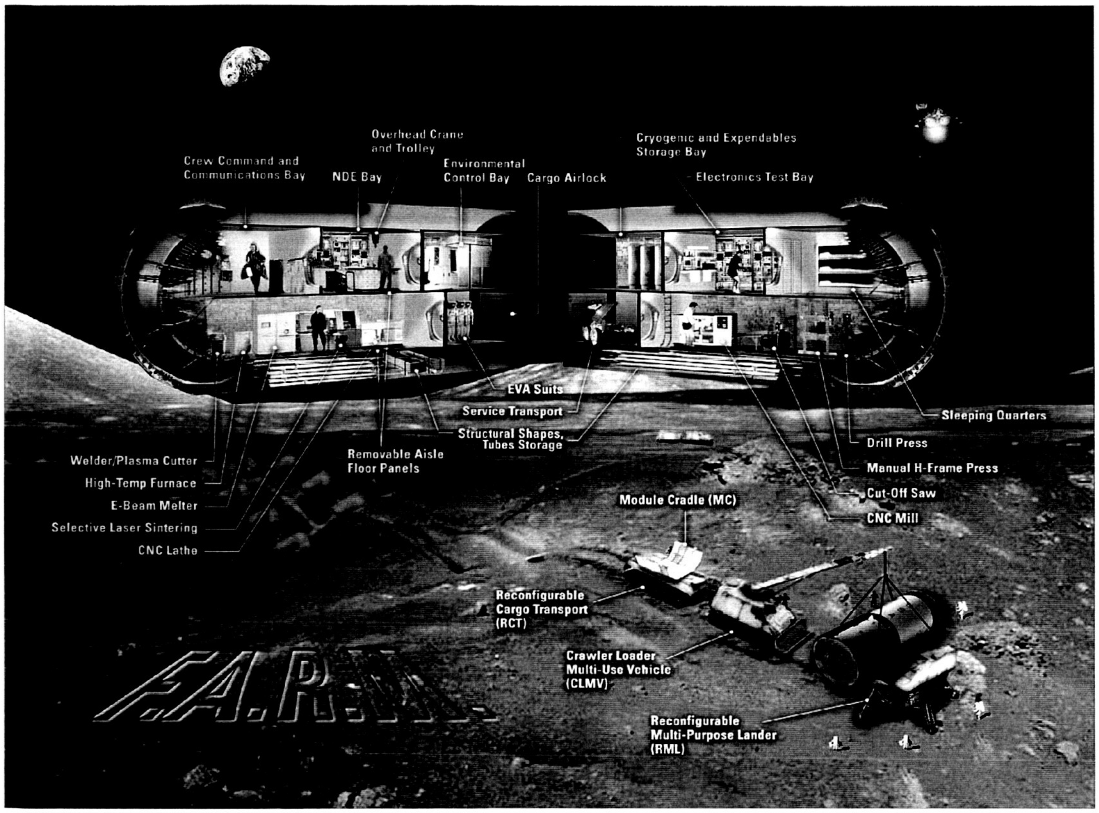

Figure 4. ISFR Fabrication, Assembly and Repair Module (FARM)

Ongoing ISFR activities include completion of trade studies and Concept of Operations documents, and then a series of Technology Selection workshops. The Technology Selection Workshops will be conducted for the purpose of selecting from a proposed set of candidate technologies those that are most likely to meet customer needs and providing the basis and authority for the selected technologies to move into the first phase of competing technology developments. Technologies should be at a readiness level of TRL 2 or 3 at this point to be included in the workshop activity. This will be followed by the technology development phase where appropriate design, prototyping, and test efforts are accomplished to provide the basis for further evaluation and down selection at one or more annual Technology Progress Reviews.

This is the beginning of a very long journey, full of challenges. However, as the current state of the art continues to advance, these far-out concepts will become part of the reality of space exploration. And, as we continue to focus on new technology advancements, it will become apparent to all that the future really is "Out of this World"!

Acknowledgments

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