In-Situ Rapid Spares Manufacturing
and Its Application to Human Space Missions.

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Maintaining the performance of logistically isolated systems yield serious support difficulties. In the perspective of a Human mission to Mars, it is known that the ability to maintain systems will be a key issue and that spare parts might pose some problems. Usual solutions consider improvements in reliability and fault-tolerance, storage of carefully selected parts, potential resupply missions, or a combination of these strategies. In this article, we propose a different approach. Having noted an analogy between physiology and the manufacture of parts, we consider the use of rapid-prototyping and manufacturing techniques to replace, on-site, a failed element by a palliative one, intended for temporary repairs or not. The system can then be restored to an acceptable level of performance so as to continue the mission, or wait for a more permanent repair. However interesting the concept is, some questions must be raised regarding technical feasibility, as well as reliability and safety impacts on the mission itself. The article is organised as follows. A first part describes briefly supply support methods and highlight their characteristics. A second part proposes and discusses the rapid spares manufacturing concept. The contribution of rapid prototyping techniques is evaluated in a third part and illustrated as an example. The last part indicates research perspectives linked with in-situ resources utilisation, as well as the qualification process for such spares.

Supply chains of distant exploration missions

First let's define what we understand under the term "logistically isolated". A system is logistically isolated whenever external conditions rule the supply operations. Several systems answer to such a definition : arctic missions, oil platforms, and of course, inhabited space missions. Logistics support of human space missions are about providing the resources needed to support the crew, the systems, and the scientific users throughout the mission [Gre99]. Crew support consists of items required to directly support the crew, such as consumables, food, clothes, accommodations and personal items. User support includes items needed to support

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requirements for performing science, such as tools, refrigerated containers, etc. Systems support includes mainly spares and repair parts, consumables, as well as tools and documentation. In the case of the Freedom space station (it shouldn't change drastically for the International Space Station), it was estimated that for a typical resupply mission, the two most significant items were science items (33%) and maintenance items (27%), then came crew accommodations (18%), propellant (14%), and cryogenics (8%). A reasonable rule of thumb for estimating the mass of spares needed per year of operations seems to be 5% of dry mass per year [Lea93]. The recent NASA reference Mars mission scenario estimates for spares are very similar (6%) [Nas97]. Although maintenance problems for Mars missions seem to be focused on crew time and systems health monitoring, it might be more realistic to believe it is fault-tolerance and the ability to repair that will be key. As J.L Chretien, one of the French astronauts, said concerning Mars missions : "Why do you want me to cross a desert in a car I know I cannot repair ?" [Qes94]. It is known that risks usually make spares the most visible part of logistics support problems [Cha98] and going with the wrong spares, or even level of spares, can impair seriously both mission performance and budget. It can readily be seen that they will also take volume and mass off the mission budget. It is therefore important to understand that if we want to achieve a Mars mission, such issues need to be addressed early.

Strategy	Description
Carry-along	All supplies required for the mission duration are brought with the spacecraft
Planned rendez-vous	Supplies are sent to the mission site before/after the crew arrives
Pre-position	Resources are stored for a given period of time then resupplied
Live off-the-land	Supplies are produced on-site, mainly using local resources

Table 1 : Supply strategies to provide the mission resources

Establishing a supply support concept is difficult. It is a compromise among many variables arbitrated by past experience with similar systems. How to select the elements to spare? In which quantity? Two main rules emerge regarding spares: plan what is foreseeable, and prepare for the unexpected. The main issue seems, to our understanding, to focus on the length of acceptable functional degradation. Some items are obvious spares candidates, for example elements with a limited useful life (e.g. filters), but what of the others? The truth is that we would like to either bring a bit of everything...or have no need for spares at all! Since it is not feasible yet to go without spares, several strategies have been established to provide such resources. Note that these strategies consider resources in general, not specifically maintenance resources such as spares (cf. table 1). While carry-along, planned rendez-vous, and pre-position strategies are usually envisioned, their advantages seems to weaken when the supply chain becomes very tight with delays, as is the case in a Mars mission. To face unforeseen situations seems very difficult with these strategies only. It seems to us logical and reasonable to use live-off the land strategies for maintenance too, and to provide the crew with the means to repair "virtually" anything that needs to be repaired. Most of the time failure does not mean the end of the mission, but a degraded state. What would be needed then are means to either repair or stay in acceptable states pending a repair. It struck us as one system is able to do this to some respect : the human body.

Supply chains analogy

The human body is able to sustain a wide variety of "failures" for varying duration. Simplifying the real physiological process, one can say that the "repair" process is made of two distinct parts. To understand this, one can take the example provided by the rupture of a small blood vessel. The first part of the process seeks to maintain the function (circulation of blood). Vaso-constriction of the vessel and fall of pressure slows the blood flux, and immediately a seal is started. In a second time, when the situation is stable, the body starts building new skin [Sch99]. We made several observations concerning this repair process. First of all is the known concept of palliative repairs while waiting for more permanent ones. It suggests strongly that what is important is to maintain the function, even degraded, but not necessarily the elements. It also suggests that under resources constraints, it appears logical to provide enough time for the repair process to take place. Secondly, it is striking to see that there are no "spare parts" per say, but a knowledge of how to create the "failed" part, skin cells in the human analogy. This knowledge is contained in the genetic materials and encompass the parts information, as well as the manufacturing process. The body adapts itself to gather enough energy in order to perform the repair process. Of course, the damages are sometimes too extreme to be fixed via this process.

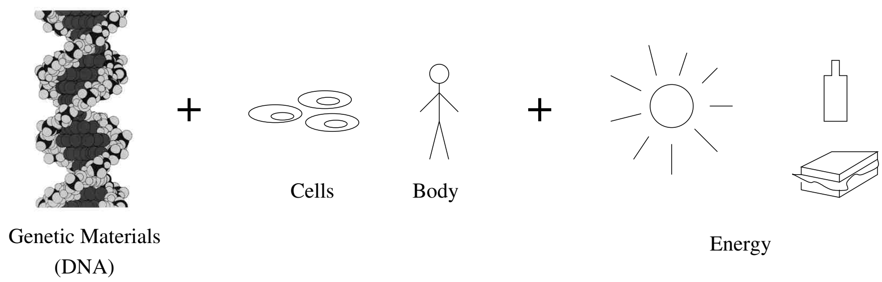

Fig.1 : Simplified skin repair process

We have tried to make analogies between these two observations and the repair process of technical systems. Though one could think of nano-machines to perform precisely what the body achieves, this technology is not ready yet and we choose to take a look at readily available technologies. The human body uses instructions contained in genetic materials, as well as internal resources (cells, energy, etc.) to build the needed elements (cf. fig.1). The analogy with Computer Aided Manufacturing (CAM) appears striking. In such a methodology, one uses data in the form of Computer Aided Drawings (CAD) and instructions for the numerical machining tools, as well as other resources such as machines, energy, raw materials (cf. fig.2).

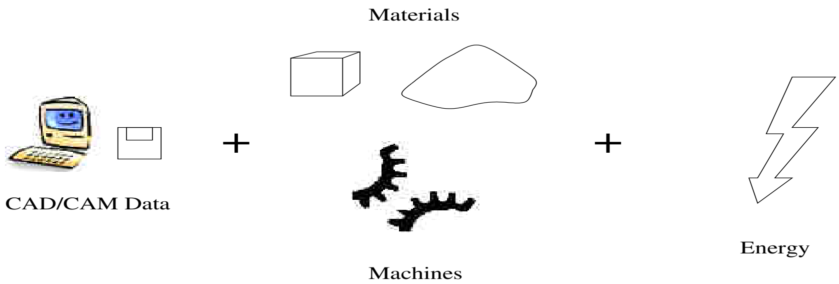

Fig.2 : Simplified manufacturing process for an element

One might then be inspired by this analogy to achieve for a technical system what Nature achieves for a biological one. In that perspective, it is possible to imagine replacing a failed element by a palliative one manufactured on demand to provide time to the system that could be used either to finish the mission, wait for an incoming resupply cargo, or manufacture a permanent repair part. What we then imagined is to be able to manufacture, on demand and on-site, the needed parts, using CAD/CAM files and a pool of raw materials. As of today, it is not realistic to believe all elements are rapid spares candidates, for operational or technological reasons. A list of potential candidate elements has to be established. Although this might change on Mars, it is not mechanical parts that fail the most. However, it is the mechanical structure of an element that usually have the main share of the mass. At the same time, mechanical parts are the ones not spared, but whose failure can impair the mission. A broken fender on Apollo XVII Moon rover had dust showering crew and equipment, but was repaired...with a spare lunar map and clamps [Mel97]. While we consider mainly mechanical elements in this article, it might be possible to go further than just manufacture the structure when considering programmable chips, hardware-independent design techniques (e.g. VHSIC Hardware Descriptive language, or VHDL), standardisation, or Evolvable Hardware [San96]. Note that very recent research in France made plastic transistors possible [Gar99].

Achieving a workable concept

Rapid prototyping and rapid manufacturing techniques allow parts manufacture with a rich and complex variety of shapes. Deviated from their original purpose, they might be a good solution to manufacture swiftly any needed spare parts. By definition, rapid prototyping means "manufacturing of models and prototypes" and qualifies the process to restitute physically 3D objects described by their CAD data, without tooling, and in a fraction of the time required by classical manufacturing techniques [Ber98]. Manufacturing such objects is made by an iterative supply of materials, as opposed to rapid manufacturing techniques which are based on removing materials. By principle, these methods are targeted at very small series, even single units. It is important to note that in the case of rapid prototyping there are no waste of raw materials, while with rapid manufacturing there is a production of chippings which are not useable afterwards. The energy required for the two methods are also very different, in the favour of rapid prototyping. Therefore we chose to focus on rapid prototyping. The rapid prototyping process is based on a digital description of the object in slices. Starting from the 3D surface or solid model, parallel sections are computed perpendicular to the machining direction. The spacing between slices corresponds to the thickness of material creation. 2D descriptions provide the contours and the mean to distinguish between internal and external areas. The adjunction of material is done on the previous slice via solidification of a resin or a thermo-melting material, via agglomeration of powders, or via gluing of sheets of materials. It is possible either to construct the objects point-by-point (laser-based systems), or one slice at a time (mask and lamp-based systems). The majority of the processes relies on a change of state of the material (liquid to solid). Typically, a monomer resin is used : starting with a tank filled of resin, the object is built layer after layer, to obtain the element at the end of the process. The largest parts obtained so far, to our knowledge, are around 600 x 600 x 500 mm3. The main dimensional limitations come from the volume of the supply tank as well as the methods used. Other methods (powder to solid) use thermal processes instead of photo-chemical ones and use all kinds of materials. Cutting and laminating methods are the only ones that do not rely on a change of state : sheets (paper, plastic, etc.) are cut, piled, and glued together. As to the required energy budget, a brief review of the available tools indicate that 500W should be more than sufficient (nothing compared to classical techniques). The tooling required, we estimated, should not take more than 1 or 2m3. The overall mass of raw material needed will depend on the range of the candidate elements. Note that these data are for machines not optimised for a space application.

The main difficulties and drawbacks of these methods are the quality of the obtained parts. For example, only specific resins can be used, and objects obtained through thermal techniques are porous and must be post-processed. It is clear that the quality levels as to dimensions, geometry, surface, and mechanical characteristics, are not yet up to the values one would like to see for a direct use of such a part in a real system. However, it appears possible to realise mechanical elements, made from equivalent materials, that respect the functional roles of the original element. More, joint improvements of processes and raw materials allowed to manufacture metallic elements with process times divided by factors up to 20 from the classical manufacturing process. Using a specific powder it is possible to produce directly metallic elements from CAD (cf.fig.3). Reproduction of precise detail and a post-processing free method, as well as the good mechanical characteristics obtained allowed to use directly the obtained parts.

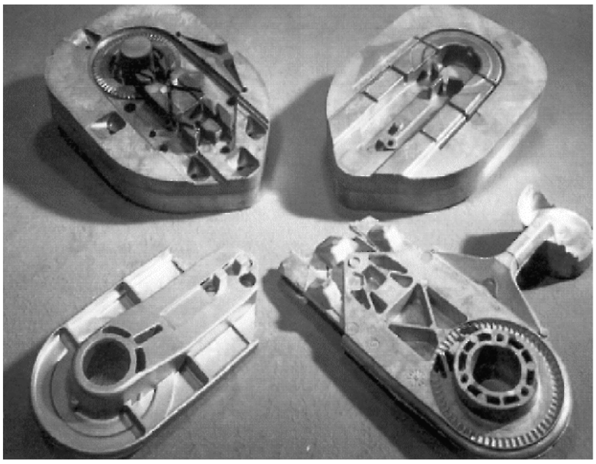

Fig.3 : Inserts produced by Direct Metal Laser Sintering of EOS GmbH. In this DirectTool™, Magnesium parts have been injected.

The interest for maintenance is then clearly with the capability to provide a part almost on demand. This suggests that it should be possible to use rapid-prototyping techniques to manufacture spare parts in such a way, being close to the analogy we proposed with Nature in a preceding part of this article. On a small scale, we recently manufactured spares for small obsolete plastic components that were used directly as replacement parts. The tooling supplies a palliative element in order to retain an acceptable level of performance, while at the same time providing means to manufacture the definitive repair part. Considering a mission to Mars, the required mass and volume required for both the tooling and raw material might well add an advantage compared to other strategies.

Research Perspectives, challenges ahead and conclusions

It is clear that the proposed concept has yet to be proven. To do so, several steps must be taken. The most important one is certainly to ascertain that the produced parts can be used as replacement elements with no added risks. It seems obvious, as said earlier, that a candidate elements list has to be established, so as to assess the impact of using a lower quality part in a real system. Another problem lies with the material that could be used and that it must qualify for use in a Space environment. A key issue is to validate the required manufacturing process in space. The effects of the gravitational differences must be assessed. Note that the tooling required could well fit into an International Standard Payload Rack (ISPR) being used for the International Space Station, which might lead to a set of experiment proposals. Another interesting aspect is to consider the use of local materials to manufacture the parts Focusing on Mars missions and the live-off-the-land strategy, it should be possible to go even further in the analogy with Nature. The perspective offered by the presented concept broadens when considering the usage of martian resources. According to several authors, one can reasonably think of producing ethylene and derived products, that is plastics, but also ceramics, and metals. The Martian environment is of radiation, low pressure, etc. One can think of using these characteristics for the manufacturing process, thus lowering the needs. Ultimately, one could think of melting the palliative part after use. It would be interesting to test martian plastic simulant in producing a palliative part.

As a conclusion to this article, one can review the main ideas behind the proposed concept. Providing the means to perform maintenance during exploration missions, such as a human mission to Mars, is a key issue. Attempting an analogy with Nature, it is believed that palliative parts can be created on-site using rapid prototyping techniques. It is certainly true that such a concept might not be used on early missions. The fact is, as said in the first part of this article, that building a supply support concept for an exploration mission is basically a mix of strategies. We believe this concept can be given a chance as a reasonable alternative for carefully selected elements in successive Mars missions, and that steps are to be taken in that direction.

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