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Envisioning e-logistics developments: Making spare parts in situ and on demand
State of the art and guidelines for future developments

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Abstract

The work aims at thinking over a concept of spare parts manufacturing on request and in a short time. This concept will concern 'isolated systems' in which the part supplying is made difficult because of the specific environment which is not really adapted and for which the storage of spare parts implies space constraints incompatible with the size of such systems. The quick spare parts manufacturing is made possible by developing new quick manufacturing technologies about to be mature today and using e-maintenance supports. The implementation of those technologies allows reproducing the defective unit, which needs to be replaced in a short time and according to the requirements.

Keywords: Spare parts manufacturing; Distant system; Logistic support; E-maintenance

1. Introduction

In order to shorten the time of immobilisation of a system having to be repaired, it is essential to have whatever the place and at any time the part needed to replace the one, which has failed. It is made possible if there is on the shelf an exhaustive and comprehensive stock of spare parts. This solution results obviously in a significant cost and is not always technically achievable. The alternative strategy is to be able to create, on demand and in situ, the part required to proceed to the maintenance intervention. In this context, the use of solid freeform technologies seems to be particularly suitable. We discuss in the paper about the integration of this concept into an isolated system whose supplying is made difficult for any reason.

The work is divided into six parts. From the decomposition of the maintenance process, we show in a first part that the time of spare parts procurement can also be reduced by the use of e-maintenance technologies. We introduce here the concept of e-logistic support and the notion of isolated system, which finds in the e-logistic support an obvious field of application in order to warrant the mission reliability level it has been made for. In a second part, the solid freeform technologies are described and classified. The concept of rapid spare parts manufacturing which is an extension of the use of the solid freeform technologies and the expected benefits for remote system are discussed in the third and fourth parts. Three studies based on industrial cases and representative of three different modes of isolation are then presented in the fifth part. Eventually, an organisation of the fields to be investigated in order to improve the concept and increase the industrial implementation level is proposed in the sixth and last part.

2. Problematic of spare parts procurement for distant system

2.1. Place in the maintenance process

The maintenance interventions can be divided into elementary sequences corresponding to different phases of the considered process. The corrective and preventive interventions are presented, for instance in Figs. 1 and 2.

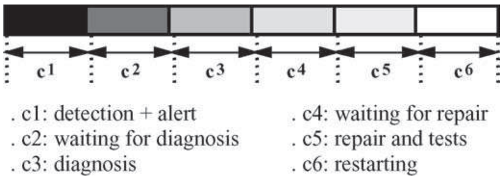

Fig. 1. Corrective maintenance process.

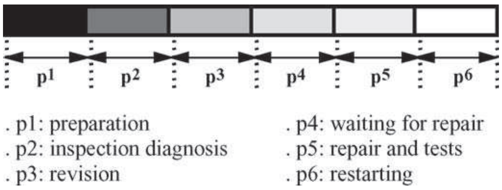

Fig. 2. Preventive maintenance process.

Let us note that this partition concerns the intervention as such but the work of preparation can start well before the machine is stopped. The interest of this decomposition lies in the fact that each sequence requires different material and human resources. If most of the operations are realised by internal means, some of them call for external resources and skills (supplying of spare parts, subcontracting of operations, . . .). The e-maintenance techniques can be of great help during the intervention but this added value is inequitably distributed over the process phases (Cf., Table 1).

The notion of e-service has an influence on the process sequences that is mostly improved in term of time spent in each phase and quality of the carried out actions:

- phase C1 is made more efficient and fast by a constant monitoring from distant work stations adapted to a proactive information processing. Remote monitoring makes possible the prevention of the failure by observation of the system behaviour;
- phase C2 exists when diagnosis resources are unavailable. This phase can be reduced or even suppressed by the way of hot lines able to analyse the dysfunction from the information received;
- phase C3 can be improved in term of fastness and accuracy by the e-techniques: remote analysis of the symptoms of failure through consultation of an expert or a network of experts, procurement of documentation, possibility for the operator to follow a research procedure provided by softwares or external sources;
- phase C4 is few influenced by the e-maintenance concept since it corresponds most often to a repairman unavailability or a wait for a physical resource to be delivered (spare part, tooling . . .). The only benefits, small ones, concern the e-management of stores like, for instance the purchase order of a spare part automatically generated when the premises of a failure appear;
- phases C5 and C6 are also directly concerned by e-maintenance services: assistance of local operators in order that they carry out the intervention, support of e-documentation but also remote control of the maintenance tasks (repair, restart) through some modes of teleoperation.

Table 1
Localisation of e-maintenance services onto the corrective process

C1 detection + alert	E-detection Monitoring and tests, remote consultation of alarms
C2 waiting for diagnosis	E-assistance Call centre, Customer relationship management
C3 diagnosis	E-diagnostic E-documentation, expert systems and networks
C4 waiting for repair	No effect
C5 repair and tests	E-control Operator assistance, teleoperation
C6 restarting	E-information E-documentation for tests and adjustments

Let us add also the possibility of e-learning or e-training offered by these techniques to the field of maintenance. The same analysis can be done with the maintenance preventive process (phases P1–P6) since it has been shown in Fig. 2 that during the inspection (phases P2 and P3) a hidden failure could be identified leading to carry out the phases P4 and P5 as in the corrective process.

As a result, one can see that the e-maintenance gains are linked with an increase of availability level through constant monitoring, better control of diagnosis and repair processes, possibility to perform remote actions and improvement of quantity and quality of information and knowledge processing.

The phase C4 (waiting for repair) does not contribute very much in this global improvement since e-maintenance techniques seem to be unable to facilitate this phase. Based on this observation, we propose in this paper a different form of spare parts management. We focus in particular on isolated systems and will describe new manufacturing techniques likely to integrate some forms of e-maintenance. We will call this concept e-logistic support.

2.2. *Notion of isolated systems*

A system is considered as isolated if the time needed to supply it with the items required for its proper functioning leads to a waiting time incompatible with the mission planning. In Ref. [7], the authors explain that ‘‘a system is logistically isolated whenever external conditions rule the supply operations’’. The items to be supplied can be dedicated to the system itself (spare parts, consumables, tools, documentation, . . .) as well as the crew or the staff in charge to pilot or use the system (food, clothes, personal gears, . . .).

Two forms of isolation are possible. First, a system can be geographically isolated, e.g. when accessibility is difficult because of:

- the lack of communication (polar regions, high mountains, thick forests, . . .);
- the nature of the environment (air, sea, space, . . .);

- the possible in site risks (battle field, epidemiological areas, grounds where natural disasters can occur).

A system can also be temporarily isolated, e.g. when the system is dependent on elements likely to disappear at the end of a given period of time (closure of production lines for profitability reasons due to the low-volumes still in the market . . .).

With regard to spare parts management and in order not to be affected by the isolation problem a solution consists in having at one's disposal the needed part whenever or wherever. It may be possible if there is an exhaustive and well enough supplied stock of spare parts. But it is an expensive solution, especially if the system is complex and consists of a large number of parts; furthermore it is not always possible, e.g. for lack of room.

We present following some examples of systems operating in an environment propitious to the use of such processes:

- Orbital station (International Space Station–ISS, late Mir . . .): the small area of each laboratory does not make possible to store a large number of space parts. Furthermore, the every 2 months supply of the ISS, the constraints depending on the American shuttle in charge of supplying the spare parts (it is impossible to load the shuttle 45 days before its take-off for planning and trimming reasons, the limited weight and volume that can be carried) are factors in favour of an in site making of the replacement organs. In the ISS particular case, it could be contemplated to devise a multi purpose machine that could make spare parts of the five laboratories, which would reduce the clutter inside the station. Similar problems can occur in submarines, frigates, aircraft carriers, oil rigs, . . .;
- Military equipment (tanks, gun ships, radar vehicles, . . .): in case of fights in confined-spaces, military instructions stipulate the destruction of any piece of equipment that cannot be brought back and that the enemy could appropriate. The high costs at stake – more than 4.573.500 € for a Leclerc tank, for instance – prompt military authorities to set up rear lines logistics capable to repair the equipment if necessary. By definition, the mobile feature of this type of equipment does not make possible the transportation of a complete set of spare parts. An in site making of the part in question by means of a portable technology of rapid manufacturing could be a profitable solution. Similarly, from a problematical point of view, Thomson is thinking about the rapid manufacturing of spare electronic components for repairing printed circuit boards, integrated circuits, . . .;
- Old equipment (vehicles, household appliances, computer equipment, . . .): the protracted use of some old equipment compels their manufacturers to commit themselves to provide spare parts long after the production of the equipment has been stopped in order to meet their customers requests. This can be obtained either by keeping their production lines in an operation state or by making in advance a large number of parts stored in wait to be used for replacing failing organs. This imperious requirement is very constraining as far as both solutions are very expensive, which entails to pass a price increase to be paid by the customer. Then the use of the new technologies of rapid manufacturing would meet the demands of spare parts while limiting the number of the parts stored in the expectation of such demands and while keeping in operation only those production lines whose output is deemed sufficient to justify their activity.

3. Solid freeform fabrication

The alternative solution to the problem of spare part supplying is to make on request and on the spot, the substitute needed for the corrective or preventive maintenance. We present in this section some technologies likely to respond to this demanding context.

3.1. Principles

Three-dimensional rapid prototyping and manufacturing (3DRPM) is the name given to a host of related technologies that are used to fabricate physical objects directly from CAD data sources. Opposed to a conventional machining process, which takes away excess material from a block of workpiece, 3DRPM produce parts by building one layer upon another in an horizontal manner. Such systems are also known by the general names solid freeform fabrication and layered manufacturing and offer advantages in many applications compared to classical subtractive fabrication methods, such as milling or turning:[1]

- Objects can be formed with any geometric complexity or intricacy without the need for elaborate machine set up or final assembly;
- Objects can be made from multiple materials, or as composites, or materials can even be varied in a controlled fashion at any location in an object;
- Solid freeform fabrication systems reduce the construction of complex objects to a manageable, straightforward, and relatively fast process;
- Jigs and fixtures are no longer needed.

These properties have resulted in their wide use as a way to reduce time to market in manufacturing. Today's systems are heavily used by engineers to better understand and communicate their product designs as well as to make rapid tooling to manufacture those products. Surgeons, architects, artists and individuals from many other disciplines also routinely use the technology.

Rapid prototyping is not a solution to every part fabrication problem. After all, CNC technology is economical, widely understood and available, offers wide material selection and excellent accuracy. However, if the requirement involves producing a part or object of even moderately complex

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[1] Most of the description and pictures which appear in this section are courtesy of Castle Island Corporation. The Worldwide Guide to Rapid Prototyping http://home.att.net/∼castleisland/.

Table 2
State of the art of the solid freeform fabrication techniques

Liquids	Photocurable liquids	Curing by light through masks Curing with a visible light laser Curing with an UV-laser (single beam) Curing with two laser beams simultaneously Curing by visible light with a dvd-device Hybrid, combining inkjet-technique and curing with an UV-lamp
	Electrical conducting liquid	Electroplating
	Water	Freezing of water
Powders	Melting of powder	Sintering with a heat transferring laser Melting with a heat transferring laser Using conventional sintering and hip
	Binding powder by adhesives	Methods based on 3D printing Extrusion of ceramics with melted binder
Solid materials	Extrusion of melted material	Extrusion of plastics Methods based on welding Spraying of metal Extrusion & milling of multiple materials Inkjet techniques
Sheets	Bond-first lamination	Cutting material with a laser Cutting material with a knife Cutting material with a milling machine
	Cut-first lamination	Cutting material with a laser Cutting material by water Cutting material with a knife Cutting material with a heated electrode Cutting material with a milling machine
Gas, atoms and other odd stuff		Gas Individual atoms or molecules

geometry, and doing so quickly—RP has the advantage. It is very easy to look at extreme cases and make a determination of which technology route to pursue, CNC or RP. For many others less extreme cases the selection crossover line is hazy, moves all the time, and depends on a number of variably weighted, case-dependent factors. While the accuracy of rapid prototyping is not generally as good as CNC, it is adequate today for a wide range of exacting applications. The materials used in rapid prototyping are limited and dependent on the method chosen. However, the range and properties available are growing quickly. Numerous plastics, ceramics, metals ranging from stainless steel to titanium, and wood-like paper are available. At any rate, numerous secondary processes are available to convert patterns made in a rapid prototyping process to final materials or tools.

3.2. Technical means

There are currently no less than 30 different 3DRPM [21]. We present in the Section 3.2.1 the different families of techniques before describing in a more detailed manner and in a second paragraph some of the major technologies currently used around the world.

3.2.1. Families of 3DRPM techniques

These still new techniques – the oldest is only 16 years old – are based on assembling matters layer by layer by physical or chemical transformations [13]. The manipulated materials are either liquid (resin) or solid (of one-dimension: powders, of two-dimensions: sheets or of three-dimensions: plates). The transformation process, in which the section obtaining operation must be distinguished from the previous sections assembling operation, can be made without changing the state of the material (cutting and piling-up) or through a state change (melting, polymerisation, gluing and welding). The methods presented in this section are mostly sorted by nature of material.[2] (Table 2).

3.2.2. Major technologies

An other way to classify the technologies would have been to take the angle of the process used to manipulate the material, namely polymerisation, sintering, cutting, extrusion, bonding, …. In order to make easier the global understanding of the different techniques, we present following, the main technologies belonging to each of these five categories.

3.2.2.1. Polymerisation by stereolithography [1,9,14]. A moveable table or elevator (A), is placed initially at a position just below the surface of a vat (B) filled with liquid photopolymer resin (C). This material has the property that

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[2] The reader is invited to consult http://ltk.hut.fi/~koukka/RP/rptree.html for more details.

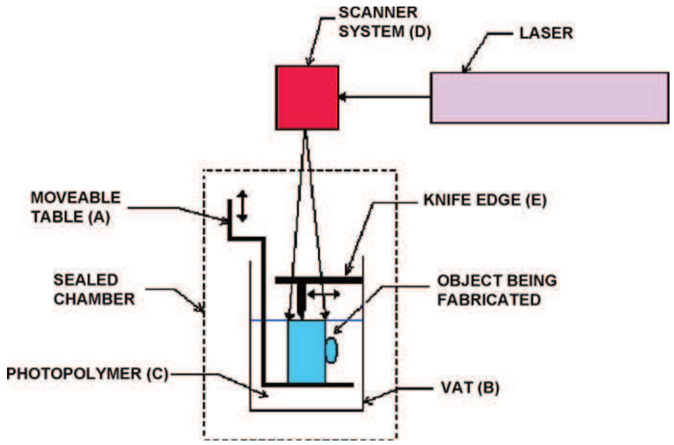

Fig. 3. Stereolithography.

when light of the correct colour strikes it, it turns from a liquid to a solid. A laser beam is moved over the surface of the liquid photopolymer to trace the geometry of the cross-section of the object. This causes the liquid to harden in areas where the laser strikes. The laser beam is moved in the X–Y directions by a scanner system (D). Fast and highly controllable motors drive mirrors and are guided by information from the CAD data. After the layer is completely traced and for the most part hardened by the laser beam, the table is lowered into the vat a distance equal to the thickness of a layer. The tracing and recoating steps are repeated until the object is completely fabricated and sits on the table within the vat (Fig. 3).

3.2.2.2. Selective laser sintering [4,5]. The process is somewhat similar to stereolithography in principle as can be seen from Fig. 4. In this case, however, a laser beam is traced over the surface of a tightly compacted powder made of thermoplastic material (A). The powder is spread by a roller (B) over the surface of a build cylinder (C). A piston (D) moves down one object layer thickness to accommodate the layer of powder. Heat from the laser melts the powder where it strikes under guidance of the scanner system (F). The CO_2 laser used provides a concentrated infrared heating beam. The entire fabrication chamber is sealed and maintained at a temperature just below the melting point of the plastic powder. Thus, heat from the laser need only elevate the temperature slightly to cause sintering, greatly speeding the process. After the object is fully formed, the piston is raised to elevate the object. Excess powder is simply brushed away and final manual finishing may be carried out. Depending on the application, it may be necessary to infiltrate the object with another material to improve mechanical characteristics.

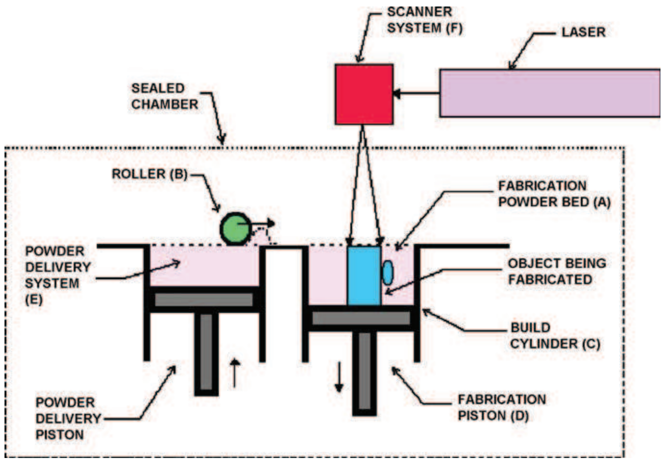

Fig. 4. Selective laser sintering.

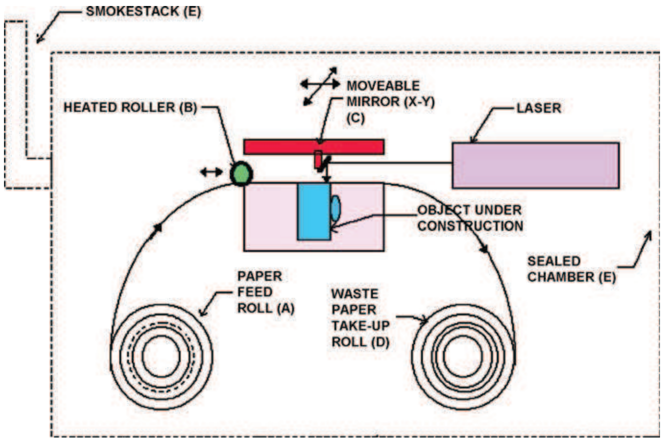

Fig. 5. Laminated object manufacturing.

3.2.2.3. Laminated object manufacturing [15]. Profiles of object cross sections are cut from paper using a laser as shown in Fig. 5. The paper is unwound from a feed roll (A) onto the stack and bonded to the previous layer using a heated roller (B). The roller melts a plastic coating on the bottom side of the paper to create the bond. The profiles are traced by an optics system that is mounted to an X–Y stage (C). After cutting the geometric features of a layer is completed, the excess paper is cut away to separate the layer from the web. The extra paper of the web is wound on a take-up roll (D).

3.2.2.4. Fused deposition modelling [2,23]. Fused deposition modelling (FDM) is the second most widely used rapid prototyping technology, after stereolithography. As shown in Fig. 6, a plastic filament, approximately 1/16 inch in diameter, is unwound from a coil (A) and supplies material to an

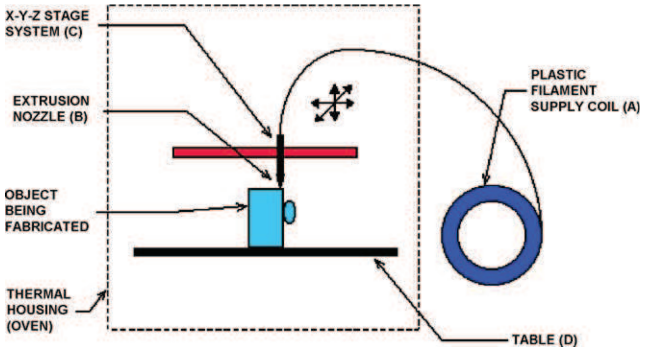

Fig. 6. Fused deposition modeling.

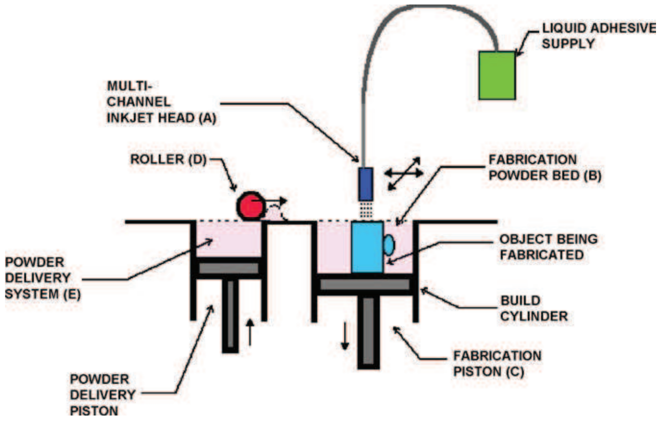

Fig. 7. Three-dimensional printing.

extrusion nozzle (B). Some lower-cost configurations of the machinery use plastic pellets fed from a hopper rather than a filament. The nozzle is heated to melt the plastic and has a mechanism, which allows the flow of the melted plastic to be controlled. The nozzle is mounted to a mechanical stage (C), which can be moved in horizontal and vertical directions. As the nozzle is moved over the table (D) in the required geometry, it deposits a thin bead of extruded plastic to form each layer. The plastic hardens immediately after being squirted from the nozzle and bonds to the layer below.

3.2.2.5. Three-dimensional printing [12,22]. The system was developed at MIT and is shown schematically in Fig. 7. The method is very reminiscent of selective laser sintering, except that the laser is replaced by an inkjet head. The multi-channel jetting head (A) deposits a liquid adhesive compound onto the top layer of a bed of powder object material (B). The particles of the powder become bonded in the areas where the adhesive is deposited. Once a layer is completed the piston (C) moves down by the thickness of a layer. The process is repeated until the entire object is completed within the powder bed. After completion the object is elevated and the extra powder brushed away leaving a ‘‘green’’ object.

4. Extension of rapid prototyping

4.1. Rapid tooling

The nature of materials used by rapid prototyping machines still suffers some limitations. It is easy to understand that resin, paper, powder have different textures, which makes difficult some validations, especially those related to the mechanical strength or thermal resistance of the product. For these reasons, the prototype can be used as a model to make moulds for plastic or metallic parts manufacturing. A new concept, the rapid tooling – two versions of which are now available – appeared. The first one has just been described: the mould making is accelerated by working out – in a very short time and from rapid prototyping techniques – the model which will be used to make it [16]. The second one benefits from rapid prototyping researches: these researches are progressing and today permit to manipulate metallic materials. Thanks to this technological advance, the newly developed technologies are not only used to making prototypes but can also be used to making moulds for plastic injection [10,11,19].

4.2. Direct manufacturing

As far as the materials used by rapid prototyping materials have similar properties to those of the material of the final product, there is a new opening, which machine makers rushed into. It deals with the low-volume production of parts through technologies originally called rapid prototyping. This idea, which has gained ground started the rapid manufacturing era.

This research work is essentially stimulated by industrial developments and concrete applications conducted by industrialists having at their disposal rapid manufacturing resources. In a near future, rapid prototyping will be synonymous with ‘‘rapid manufacturing’’. Nevertheless, today in most applications it is not possible to tackle this direct approach for reasons of manufacturing speed, part sizes, surface states of the finished parts, even of limits due to the materials used. However, there are already some examples, which prove the economical interest of this direct rapid manufacturing process.

In only 2 days, the American specialist of systems for the space industry, Rocket dyne/Boeing manufactured 200 parts made of a material – a glass fibre reinforced polyamide – whose properties were recognised suitable for critical applications. Two other days were sufficient for the American specialists for assembling the parts of the electrical subassemblies of the space stations. These ‘‘genuine’’ parts have no cause to be envious of parts manufactured by classical means, but for a beneficial decrease in prime costs and production delays. Indeed the alternative solution – making an injection mould – would have required a 4 months’ work and at least € 25,000. The space industry is convinced of the benefits of this technique. The company conducts other express manufacturing projects, such as those of plastic pipes or air ducts installed in space shuttles. The Rocket dyne specialists have so far manufactured several parts with the same selective laser sintering machine and the cost of each part was € 600. The comparison of this cost with the US € 17,600 speaks for itself, even if additional benefits, surprising and not at all negligible, are not taken into account. The American engineers were happy to find that each part manufactured by means of the rapid prototyping machine was 700 g lighter than those obtained through classical means. And when one bears in mind that a weight reduction of half a kilogram entails a shuttle cost lowering of € 6400, the calculation is made very rapidly.

Nowadays, technological researches make possible by adding some material to obtain plastic or metallic parts that can be directly integrated into industrial processes (12). Today the achieved results are obviously only the premises of drastic changes of age old manufacturing practices. Characteristics of manufactured parts have so far achieved only a medium degree of excellence, but this technique foretells a revolutionary change in the area of mechanical engineering.

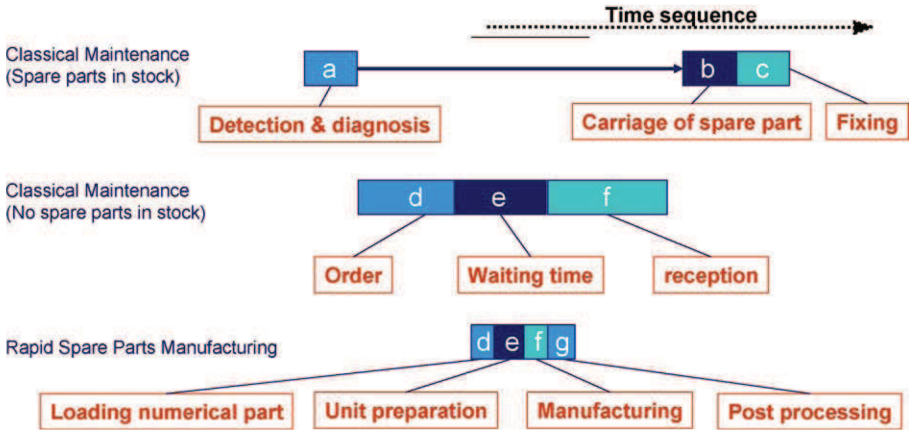

Fig. 8. Comparison of time distribution for various strategies of spare parts procurement.

4.3. *Rapid spare parts manufacturing concept*

As we have seen in the previous sections, most researches conducted by industrialists are concerned by the development phase of the product (design, industrialisation, manufacture). We wish to extend this rapid development concept to the exploitation phase of the product when used in its normal technical environment. Within this frame, we intend to investigate the additive techniques with a view of rapid spare parts manufacturing. As far as the maturing level of the processes allows contemplating the use in industrial systems of parts proceeding from additive techniques, it can be thought to make spare elements through the same principles. The idea of rapid spare parts manufacturing could even be more efficient than the concept of direct manufacturing.

Actually the prototyping techniques find difficulties to be used as direct manufacturing techniques because of the machine rates, which are not compatible with the volumes and rhythms of the current strategies oriented toward just-in-time concepts. An economical study performed within the framework of a project carried out by Alstom about the manufacturing of a specific part[3] has shown, for instance that the process with the greatest saving for manufacturing more than 15 parts did not involve the use of rapid prototyping techniques. This problem does not exist at the level of spares that are most often made one by one with lower time constraints.

This concept could find a natural field of application in two specific cases. The first is logically concerned with the replacement of organs made by adding material and damaged or reaching the end of their life. The concept of rapid spare parts manufacturing would only be an extension of the rapid manufacturing concept; it will not be considered in this paper. The second is linked with environments in which the delivery of spare parts poses problems. This situation brings back to the notion of isolated system. In the context of spare parts manufacturing, technologies operating through material adding seems therefore relevant for various reasons:

- Due to their nature, these technologies are fast and can be adapted to the reactivity need inherent in the resumption of the operation of the system by replacing a faulty component.
- They are also self-sufficient in so far nearly no intermediary operation takes place between the digital file making and the part making.
- Once the manufacture is launched, no operator has to supervise the work in progress.
- They make possible to achieve excellent identical parts because of the automated process.
- In some cases they can be multi-purpose and can be used to work out parts made of various materials (plastics, metal, ceramics, . . .).
- Most of them need only raw materials from which several articles will be made irrespectively of their functionality.
- Implementation of these technologies does not usually require bulky machines for which large floor room is necessary, but portable ones.

These criteria are strong reasons for using additive technologies to make spare parts.

5. Expected benefits

5.1. *Time aspects*

The main improvement to be noted concerns obviously the time of repair. As a matter of fact, the use of such a technology greatly fosters the global maintainability of a system, whether it is isolated geographically or temporally. An industrial system whose spare parts are not produced anymore (temporally isolated) has a very low maintainability level. If spare parts become available again to maintain the system on demand, this parameter becomes very high. In Fig. 8 a comparison is made between classical maintenance strategies with and without spare parts in stock and the strategy based on the rapid spare parts manufacturing concept.

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[3] http://www.lboro.ac.uk/departments/mm/research/rapid–manufacturing/consortium/case/Alstom_Tube.pdf.

The scale of Fig. 8 does not represent the important benefits in term of maintainability likely to be reached when using rapid spare parts manufacturing techniques. In Ref. [17] it is calculated the number of days needed to maintain a space station sub-subsystem. Both classical maintenance methods (without any spare parts in stock) and rapid spare parts manufacturing techniques are compared. It is shown major gains in maintainability ranging from 53.5 days (56 − 2.5) for the best case to 140 days (146 − 6) for the worst case, when using an in orbit rapid spare parts manufacturing unit.

In term of e-maintenance, it is interesting to note that the technologies could be remote controlled [20]. Few changes in term of organisation and some further technological developments would make feasible:

- a distant preparation of the digital files built from the CAD data for the optimisation of the part positioning inside the vat (maximisation of the number of parts to be made, minimisation of the manufacturing time, possible design of the support structure, ...);
- a transfer of digital data through adapted networks (radio waves, optical fibber, satellite communication, ...);
- a remote control of the machine itself concerning the manufacturing tasks (all the more as the automation level of these technologies makes them nearly self-sufficient);
- a monitoring of the manufacturing operations by the way of digital camera integrated into the machines.

The machine preparation tasks (cleaning, renewal of the material level ...) as well as the part post-processing (finishing, elimination of the support structure ...) remain however, tasks devolved upon the embarked operators.

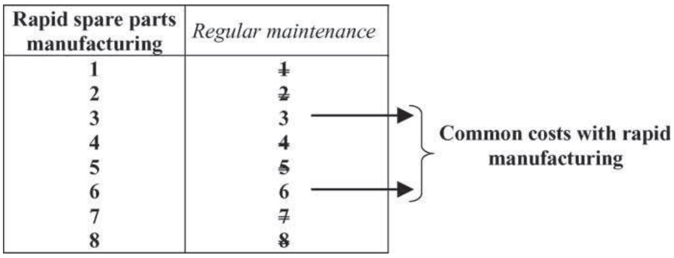
5.2. Cost aspects

5.2.1. Physical costs

The first cost aspect to be considered is the production cost of spare parts using a rapid spare part manufacturing unit versus any other means of production. An economical analysis must be done before any implementation of the system.

The global cost ownership of a rapid spare part manufacturing unit should be considered. This cost could be obtained by summing the following parameters:

(1) Costs of unit development and production (including unit and computer);
(2) Costs of unit customisation and installation (to be included in a tank or space station, to modify production instructions and to ship/launch);
(3) Costs of inputs (materials needed for spare parts production);
(4) Costs of teleoperation (if any);
(5) Costs of unit maintenance;
(6) Costs of operator training;
(7) Costs of operator's time (in monetary unit per man-hours);
(8) End-of-life costs.



Rapid spare parts manufacturing	*Regular maintenance*
1	~~1~~
2	~~2~~
3	3
4	~~4~~
5	~~5~~
6	6
7	~~7~~
8	~~8~~

If the gains procured by the system are greater than the global cost of ownership, then such a technological solution is profitable. This profitability analysis could demonstrate that it could be expensive to ship some systems because of costs (air/space fret or shipping cost per pound), staff training, initial investment (implementation studies, purchase of process, tools, machines), and even cost doubling. In such a situation, continuing the traditional supplying policies is preferable.

5.2.2. Costs of unavailability

The cost of unavailability of a system should also be considered. If the system could not be supplied with proper spare parts in time, the cost of unavailability could be very high (lost of production, lost of image, ...). Producing spare parts that are strictly necessary to maintain system global availability and efficiency is the only solution to reduce drastically storage costs and unneeded spare parts production.

5.3. Security and non-cost aspects

Some limitations concerning the previous calculations are applicable. In some specific cases, cost aspects could be considered as minor if the rapid manufacturing unit allows, for instance:

- Life sustainability (long duration space mission);
- Nation's ability to win a war (tank or helicopter);
- Or, service continuity (any temporally isolated system).

6. Premises of implementation

We now introduce three examples of use of rapid prototyping techniques to assist the operation of making spare parts within isolated systems. We start with geographic isolation. We then present a system temporally isolated because there is no longer the possibility to make spare parts. Eventually, we conclude with a type of isolation due to the level of risk which is the case of a battlefield.

6.1. Making spare parts for system difficult to access due to distance

Orbiting at 400 km above the Earth (Cf., Fig. 9), the International Space Station (ISS) is an excellent example of geographically isolated system. The only link between the

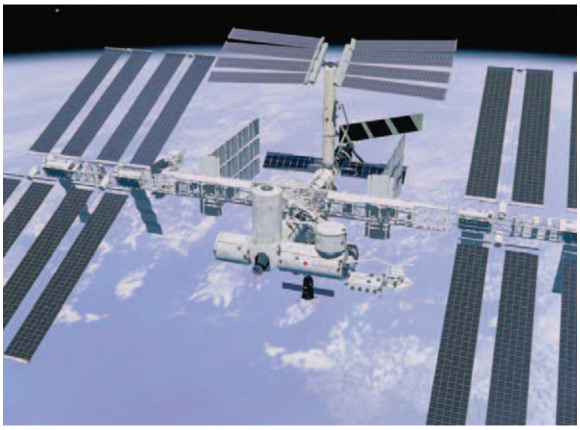


Fig. 9. The International Space Station.

station and the Earth, beside telecommunication, is the supply provided by both the Shuttle and the Soyouz Progress. The storing of each module does not make possible to store a large number of space parts [6]. Furthermore, the every 2 months supply of the ISS and the constraints depending on the American shuttle in charge of supplying the spare parts (it is impossible to load the shuttle 45 days before its take-off for planning and trimming reasons, the limited weight and volume that can be carried) are factors in favour of an in-site making of the replacement organs [3,7]. In the ISS particular case, it could be contemplated to devise a multi purpose machine that could make spare parts for all modules that would need them, which would reduce the clutter inside the station.[4]

Because of its manufacturing flexibility, solid freeform fabrication (SFF) will be of enormous value to human exploration of space. Storing a large number of replacement parts on long-duration missions – such as a journey to Mars – is impractical, and waiting for replacement parts will not be an option. SFF has a number of potential advantages over traditional machining for use in a space-based manufacturing facility, but the reduced-gravity environment imposes a unique set of design constraints on SFF systems 1. Besides materials, resolution, and throughput, additional considerations include equipment mass/complexity/power requirements, feedstock containment and handling, and the ability of a single machine to produce objects from multiple materials.

Deposition systems, such as fused deposition modelling and shape deposition manufacturing (SDM) are attractive candidates for meeting these challenges. Because they employ a very small melt volume that solidifies rapidly, these techniques are well suited to reduced-gravity operations. By adding particles to the feedstock (FDC/FDMet) and obtaining the final material properties in a second sintering step, a variety of materials can be deposited from a single piece of equipment. The Stratasys company has performed an initial evaluation of the potential for reduced-gravity manufacturing using a stock fused deposition modelling system (Stratasys FDM 1600) as well as a fluid deposition system optimised for zero-gravity operations. These systems were flown on the NASA KC-135 Reduced Gravity Aircraft in preparation for an upcoming Space Shuttle experiment.

A Stratasys FDM 1600 was recently flown aboard the NASA KC-135 Reduced Gravity Aircraft (Fig. 10). The goal of these experiments was to obtain a set of initial qualitative observations on the feasibility of using FDM in a microgravity environment. Several ABS specimens of varying geometry were fabricated during a series of 160 parabolas, each of which provided nominally 25 s of reduced gravity. The geometry of the specimens allowed observations of inter- and intra-layer bonding, unsupported structures, and dimensional stability of specimens compared with the same designs fabricated in 1 g.

The application of layered fabrication techniques turned out to be feasible for standard and some non-standard part designs in a reduced-gravity environment. Further testing and development is planned to study the interaction between a deposited melt and substrate, as well as processing limits for free spans and partial substrates.

6.2. *System difficult to access due to time*

This section illustrates the rapid spare part manufacturing concept for systems isolated in time. This is the typical problem of obsolescence that inevitably affects single unit production (which is a particular form of insulation) but also the mass production systems whose spare parts manufacture resources are not available any more after a given time beyond the production stop.

This is the case in particular of the automobile industry. Beyond the technico-economic performances of the vehicle and in order to keep its customers, a manufacturer must provide them with spare parts over a minimum amount of time. One of the major problems in the spare parts supply after the end of production comes from the incapacity of the supplier to reach this objective. Several reasons can explain this dysfunction: company liquidation, destruction of toolings, change of technologies, loss of numerical data, ...

When the equipment or the production structure does not allow the fabrication of the spare part, the manufacturer can request the realisation of new tools. This situation, very costly for the automobile company led Renault to think of the use of rapid prototyping techniques for the manufacture of spare parts in some particular cases [18].

The work, completed within the framework of a project carried out jointly with the Central School Paris consisted in testing the solid freeform manufacturing techniques for the fabrication of a steering wheel return ring of a Clio. This part is inserted on the axis of the wheel, behind it (see Fig. 11). It allows the return of the indicator handle after the bend that stops the flashing.

When the study started, 15 vehicles were immobilised due to the impossibility for the mechanics to get this part.

The return ring selected is assembled on a first generation vehicle (X57 project). In November 2001, the supplier based in

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[4] Most of the description and pictures, which appear in this section are courtesy of the Stratasys Company (http://www.stratasys.com/Global/white-paper.html).

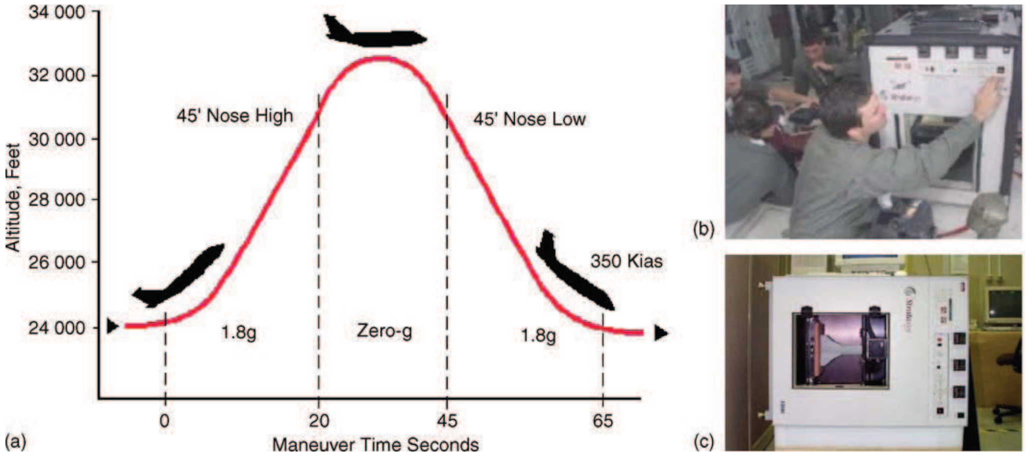

Fig. 10. (a) KC-135 aircraft trajectory. (b) Stratasys 1600 during KC-135 reduced-gravity testing. (c) Stratasys 1600 ground-based test, building parts perpendicular to gravitational field.

Turin, whose name will not be revealed here, declared that he could not provide this part anymore.

Although the manufacturing of the spares with the solid freeform technologies would have been possible it was preferred for reasons of volume, to use these techniques for the realisation of a mould made of silicon allowing the duplication of the part in as many copies as required. This is consequently a slightly new concept since we talk here about rapid tooling for spare part manufacturing. After numerical rebuilding of the part, the ring was first manufactured using the stereolithography technology. This first object was then used as a pattern for the realisation of a mould from which the spare return rings were made (Fig. 12).

The last stage consisted in checking if the parts obtained were faithful to the original parts in terms of:

(1) Mechanical characteristics. The document of the supplier giving the characteristics of the ring indicated the following mechanical constraints: matter Polyether POM or POMC or standard Polyester ABC-PC BAYBLEND T45. A plastic very similar to ABC-PC in term of mechanical characteristics was used.
(2) Thermal characteristics. A combustion speed lower than 250 mm/min in accordance with the standard ISO 3795 was recommended. The supplier of the material used did not yet carry out the tests but has a non-flammable material corresponding to these parameters.
(3) Geometrical characteristics. The part had to be faithful to the drawing with tolerances of ±0.5 mm. The whole dimensions measured on the final part turned out to be conforming to the geometrical constraints.
(4) Aesthetic characteristics: the original part being of black colour, the material used for the spare part respected the colour specification.

From this study it comes out that rapid prototyping techniques seems appropriate to the manufacture of the spare parts for the automobile industry. Compared with the unit cost of the mass produced part, the part made with solid freeform technologies turns out to be more expensive. However, the difference of costs falls with the number of ordered parts and they remain anyway much lower than the costs generated by a long duration of the vehicle immobilisation (estimated at 40 euros per day). Eventually, the first parts are obtained rather

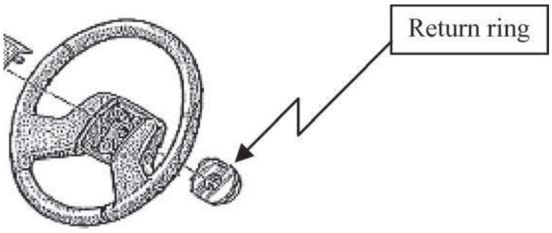

Fig. 11. Localisation of the part.

Fig. 12. Stereolithography machine and return ring patterns.

quickly, which makes possible to bring fast answers to the encountered problems.

It is necessary however to keep in mind that fast manufacture is only one alternative solution to be used to face a crisis. The aim is not to replace the traditional techniques of spare parts manufacturing and the research of more economical solutions (standardisation or adaptability of the parts, constitution of a stock likely to cover the whole demand) is still relevant today.

6.3. System difficult to access due to danger

Without being geographically out of reach, a system can be isolated because of the risk level of the considered zone. It is the case in particular of the battlefields. Modern weaponry used in this type of environment consists of a wide range of components, manufactured to high specifications, from difficult to work performance materials. This has potentially significant implications if a problem occurs with a component in front line service in a remote location. Replacement parts are often not available locally and have to be shipped in, often form another country, sometimes across entire continents. The US Army's National Automotive Centre has researched this potential weakness and developed a solution: the Mobile Parts Hospital (MPH).[5]

The Mobile Parts Hospital was developed collaboratively by the U.S. Army's National Automotive Centre (NAC) in Warren, Michigan and the Centre for Advanced Technologies at Focus: HOPE, located in Detroit, Michigan. It is a compact communications and manufacturing unit. It is designed for deployment to remote locations for emergency repair of non-operational equipment. A combination of advanced technologies enables the MPH to quickly and efficiently produce repair parts on demand. The MPH retrieves manufacturing data via satellite from an extensive solid model database of parts. In the event of no data or a communications failure, the MPH is capable of gathering its own geometric data through the use of a 3-D laser scanning system (Figs. 13 and 14).

The benefits of the MPH are:

- Flexibility, through the ability to produce wide ranges of parts on demand.
- Efficiency, because large warehouses are not needed to stock huge amounts of repair parts.
- Mobility, due to the nature of the portable facility housing the machinery.

The mission of the MPH program is to increase vehicle readiness by fabricating repair parts near the point of need. The mobile capability will include a satellite for part data transfer, hardware and software for reverse engineering, a selective laser sintering machine, and a compact vertical machining centre.

Fig. 13. The Mobile Parts Hospital.

Rapid prototyping technology is the heart of the MPH program. The MPH will embark a DTM Sinterstation 2500 as well as a Directed Material Deposition System (DMDS), made by Optomec. The selective laser sintering process was chosen because it works with a wide range of materials. The SLS machine can produce parts using metal, plastic, rubber or ceramic materials. It has a build chamber of $(x, y, z) = (15 \text{ in.} \times 13 \text{ in.} \times 18 \text{ in.})$, which is comparable to other rapid prototyping machines. The capability of the SLS machine shows that rapid prototyping is no longer limited to creating models and parts with limited functionality. Unlike the SLS process, which infiltrates its metal parts with bronze, giving the final product the mechanical properties of bronze, the Optomec machine, using laser engineered net shaping (LENS) technology, produces fully dense parts out of steel, titanium alloys, and other metals [8]. With a growing list of high strength materials, this machine will expand the production capability.

Making these machines work effectively in the field is the most difficult challenge facing the MPH program. These machines were not designed for use in a mobile environment; they were designed to sit on the floor of a spacious, climate-controlled shop.

Before the MPH is moved, measures have to be taken with each machine to ensure that they run correctly at the next stop. SLS, for instance has delicate lasers and mirrors, which have to either be reinforced or completely removed prior to moving the trailer. Once the MPH is in position the machines have to be calibrated. After having levelled the MPH, each machine must be checked individually. The calibration process for this kind of machines is usually handled by their respective manufacturers. In future developments, the calibration procedures for both

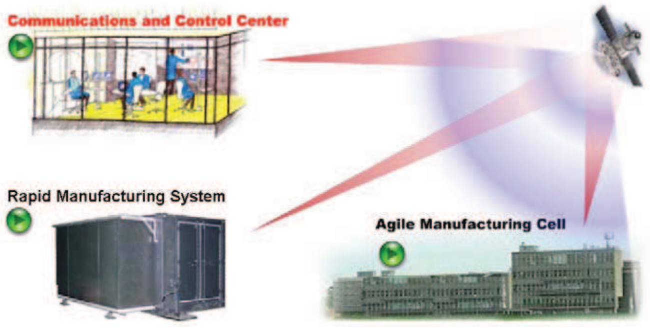

Fig. 14. Communication network.

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[5] Most of the description and pictures, which appear in this section are courtesy of The National Automotive Center U.S. Army TACOM http://www.mobilepartshospital.com/.

machines will have to be redefined so that they could be performed by the operator.

The MPH has tight size and weight constraints limiting the number of machines. The number of machines in the MPH is also restricted by the amount of power available. The problem of the electrical input necessary to perform the tasks inside the MPH will have to be tackled.

Yet another challenge facing the MPH program is the atmospheric requirements of the machines. Operating the SLS properly requires that a fairly constant temperature (15–27 °C) and low humidity ($<70\%$) be maintained around the machine. The MPH will have to be tested in both extreme cold and hot temperatures.

The U.S. Army's National Automotive Center has deployed its first Mobile Parts Hospital, a unique self-contained mobile mini-manufacturing centre to Camp Arifjan, Kuwait, in support of the American forces in Iraq. The Parts Hospital will produce a variety of critically needed replacement parts for military vehicles.

7. Fields to be investigated and research content

The fields of application presented in this paper are taking manufacturing into a new direction. Today, even the strongest rapid prototyping and manufacturing processes are inadequate to fulfil all the requirements of the spare parts manufacturing, but several processes, like selective laser sintering and directed material deposition, have made great strides in recent years. As rapid prototyping and rapid manufacturing technologies continue to mature, the rapid spare parts manufacturing concept will have to monitor new and improved processes. In the future, processes that offer a wider range of materials, faster build rates, and greater accuracy should be incorporated. We propose in this section a structure for future investigations.

There is a lot of research directions relating to the concept above described. They essentially concern two entities: on the one hand, designers and operators of systems who can be the purpose of this new rapid manufacturing approach of spare parts and on the other hand, those who engineer rapid manufacturing technologies. Within this frame several directions of investigation can be conceivable. Some are given here below.

7.1. In co-operation with the developers of industrial systems

The research work will consist in identifying the potential fields of application of this original concept and studying the feasibility of its integration and implementation in isolated systems:

- Setting-up lists of specifications representative of the constraints specific to spare elements: technical features (materials, dimension tolerances, life cycle, ...), organisational features (supplying, storing and recycling modes, ...) and economical features (whole cost ...).
- Analysis of the typologies of isolated systems and characteristic features of their structures and operating modes.
- From an organisational point of view, evaluation of the influence of the implementation of this concept thinking about the maintenance operators' qualifications and training, impact on the exploitation policy and system maintenance, consequences on the logistics support.
- Comprehensive study of the profitability, which will permit to evaluate the economical viability of these arrangements.

7.2. In co-operation with the rapid manufacturing equipment manufacturers

The investigation will deal with technological solutions that can meet the specific requirements for managing spare parts and the constraints required by the operation of isolated systems:

- Specification of the design parameters of the equipment that can be integrated in the concerned systems (technical parameters: volume, weight, resilience, reliability, life cycle, ... modes and frequencies of exploitation, nature and levels of maintenance tasks, ...).
- Characterisation of the technological solutions, which can respond to beforehand defined constraints (study of compactness of the machines, research for new material to improve the lightness of the equipment while a sufficient sturdiness is guaranteed, analysis of the dependability, ...).
- Research for operating solutions in phase with the practices and means at the disposal of users of isolated systems: study of the maintainability of rapid manufacturing equipment and its compatibility of the supporting solutions with the constraints inherent with the system, analyses aimed at improving the polyvalence of the machines: analysis of the extended range of materials used for making spare parts even of different materials, developments of processes whose reactivity fits the urgency of placing spare parts at the user disposal.

7.3. In co-operation with the users of isolated systems

The problematic will concern the complementary actions tending toward the exploitation of rapid manufacturing technologies of spare parts:

- Analysis of only functional aspects of spare elements which allow to implement a stopgap maintenance that can temporally keep the equipment operating on again until the defective function is restored by a standard change of the faulty element.
- Thinking about the conveying notions by downloading (for instance via optical networks or satellites) the definition files of the elements to be replaced.

8. Conclusion

We showed in this article how the new techniques of prototyping and direct manufacturing combined with the principles of e-maintenance could be a relevant response to the problems induced by the spare parts management of isolated systems. The preventive and corrective maintenance of the space or time isolated systems are frequently penalised by latencies caused by the unavailability of the spare parts (supplying or routing time . . .). We then investigated the idea of manufacturing on the spot and on demand, the parts required for the overhaul and repair of the equipment. We considered the rapid prototyping techniques whose inputs are raw material and numerical data corresponding to the part to be made. We proposed a state of the art focusing on the main technological solutions available and described several projects already going in the direction of our proposals. These industrial applications showed the feasibility of the concept. It is already possible to manufacture complex parts under operating conditions much more efficient than the traditional solutions of spare parts procurement which are not easily applicable to isolated systems. The fast advances made in the rapid manufacturing technological field should make possible the generalisation in the medium term of the concept of e-logistic support. In the long term there is no doubt that computers will be used to automatically manufacture objects, products and systems of every description and kind with no limit to complexity. The technologies will be reminiscent of desktop publishing, but instead of documents and printed matter, the diverse products that we need or desire to use in our lives will be manufactured for us on the spot.

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References

[1] A. Allanic, et al. Stereophotolithography: A New Step in Technology" 3rd International Conference on Rapid Prototyping, Management Development Centre, Dayton, 1992.

[2] A. Bellini, S. Guceri, Mechanical characterisation of parts fabricated using fused deposition modelling, Rapid Prototyping Journal 9 (4) (2003).

[3] R. Chabrow et al., Report of the Cost Assessment and Validation Task Force on the International Space Station, NASA Advisory Council, 1998.

[4] S. Das, J. Beama, M. Wohlert, D. Bourell, Direct laser freeform fabrication of high performance metal components, Rapid Prototyping Journal 4 (3) (1998).

[5] I. Gibson, D. Shi, Material properties and fabrication parameters in selective laser sintering process, Rapid Prototyping Journal 3 (4) (1997).

[6] J.C. Grenouilleau, Space logistics support, in: The Human Spaceflight: Mission Analysis and Design, McGraw-Hill, 1999.

[7] J.C. Grenouilleau, O. Housseini, F. Pérès, In-Situ Rapid Spares Manufacturing and Its Application to Human Space Missions. Space 2000 The 7th International Conference and Exposition on Engineering, Construction, Operations, and Business in Space, du 27 février au 2 mars 2000, Albuquerque, New Mexico, USA.

[8] M. Hedges, Advanced Repairs for Aerospace and Defense. White Paper Neotech Services MTP http://www.optomec.com.

[9] P. Jacobs, Rapid prototyping and manufacturing; fundamentals of stereolithography, Society of Manufacturing Engineers, 1992 , ISBN: 0872634256 420 pp.

[10] S. Kalpakjian, Manufacturing Processes for Engineering Material, Addison-Wesley Publishing Company, 1985.

[11] A. Kochan, Rapid developments in rapid prototyping, Assembly Automation 15 (4) (1995).

[12] S. Lee, E. Sachs, M. Cima, Layer position accuracy in powder-based rapid prototyping, Rapid Prototyping Journal 1 (4) (1995).

[13] R. Merz, et al., Shape deposition manufacturing, in: Proceedings of the solid freeform fabrication symposium, University of Texas, Austin, (1994), pp. 1–8.

[14] T. Nakagawa, J. Wei, Laser stereolithography and its applications to forming industries, Institute of Industrial Science, University of Tokyo, CMET Inc., 1994.

[15] J. Park, M. Tari, H. Hahn, Characterization of the laminated object manufacturing (LOM) process, Rapid Prototyping Journal 6 (1) (2000).

[16] F. Pérès, Using speed of rapid prototyping techniques to accelerate the tooling realization process, in: Rapid Tooling and Manufacturing, Scandinavian Conference and Exhibition, Danish Technological Institute, Aarhus Danemark, 28–29 October, 1998.

[17] F. Pérès, J. Durand, Maintainability Improvement Of Isolated Systems Through The Use Of Rapid Prototyping Techniques: A Prospective Approach, in: Esreda Seminar, Madrid, 27–28 May, 2002.

[18] F. Pérès, Analyse des Processus Alternatifs de Réalisation de Pièces de Rechange au delà des Dates de Fin de Série. Rapport de Projets de Fin d'Etudes Ecole Centrale, Paris, 2002.

[19] E. Sachs, et al., Injection molding tooling by three-dimensional printing, in: Proceedings of Rapid Prototyping and Manufacturing, Dearborn, 1996.

[20] F. Tay, Y. Khanal, K. Kwong, K. Tan, Distributed rapid prototyping—a framework for internet prototyping and manufacturing, Integrated Manufacturing Systems 12 (6) (2001).

[21] S. Upcraft, R. Fletcher, The rapid prototyping technologies, Assembly Automation 23 (4) (2003).

[22] L. Yanni, S. Lawrence, Rulebuilding: a generative approach to modeling architecture using 3D printers, Fabrication, Cambridge and Toronto, Ontario November 10–13, 2004.

[23] C. Ziemian, P. Crawn, Computer aided decision support for fused deposition modelling, Rapid Prototyping Journal 7 (3) (2001).

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