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A SURRVEY REGARDING RAPID PROTOTYPING PROCESSES APPLICATIONS IN ROBOTICS

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Abstract: *The present survey is focused on the use of RP processes in robotics and the perspectives in this area. In the first part of the article, the general characteristics of the most important layered manufacturing processes are presented and analyzed, and then significant researches in RP applications in robotics are summarized. The advantages offered by RP processes in robotics will refers mainly to the possibility to build multi-materials parts and non-assembly mechanisms, parts with insertion, and to check the mechanisms and interferences between joints.*

Key words: *rapid prototyping, rapid manufacturing, robotics, mechanisms.*

1. INTRODUCTION

Since 1987 when 3D Systems company presented and commercialized the first layer manufacturing system at Autofact show in Detroit, this group of technologies known also as Rapid Prototyping (RP) had developed heavily and steadily by increasing the number of processes, the accuracy, size and durability of prototypes, making possible the fabrication of parts as prototypes, production tools and for functional purposes.

Moreover within the past twenty years, the fields of RP applications enhanced from building prototypes for visual aids, fit/form to functional testing and end-use parts in mechanical engineering, medicine, robotics, art and architecture, etc.

Currently, the research studies in this area are focused on the following main issues: 1. Optimizing the existent RP processes, more precisely: increasing the manufacturing accuracy, automating the selection of the optimal building orientation, reducing cost and manufacturing time, enlarging the range of construction materials, developing new layer filling/forming strategies; 2. Developing new RP processes; 3. Developing new transfer formats CAD-RP; 4. Building prototypes with very large/very small dimensions; 5. Settings standards for RP industry; 6. Developing new applications for RP processes (such as manufacturing tissue scaffolds for tissue engineering); 7. Developing new software tools for optimizing RP processes; 8. Extending the Rapid Manufacturing paradigm (referred to as "Direct Digital Manufacturing", i.e. the use of additive fabrication processes to construct parts directly as finished products or components).

Regarding this last mentioned issue, it is considered that RM will gain more and more importance on the rapid prototyping and rapid tooling markets, becoming the leading trend. This will be the case also in the field of robotics, where prototypes built using different layer additive processes will be used as functional parts, for materializing different type of joints or for obtaining non-assembly robotic systems.

According to specialists' estimations [1], 25 RP processes are commercially available and more than 15 are in the research stage. Each of them has an increasing range of building materials and specific set-ups of the process parameters.

The present survey is focused on the use of RP processes in robotics and the perspectives in this area. In the first part of the article, the general characteristics of the most important layered manufacturing processes are presented and analyzed, and then significant researches in RP applications in robotics are summarized. The advantages offered by RP processes in robotics will refers mainly to the possibility to build multi-materials parts, parts with insertion and to check the mechanisms and interferences between joints.

2. RAPID PROTOTYPING GENERAL PROCESS CHAIN

In RP, the process chain starts from a digital representation of the object to be manufactured (nowadays, the literature reports two possible starting points for building a RP prototype: physical model: CT/MRI scanning data or CMM data, and computer model: 3D CAD data). This representation is converted in a neutral transfer format (namely STL), which is sent to the RP machine software and then sliced, and the data obtained are used to construct the model layer by layer. Each layer of the prototype is placed on the previous one and bond with it, in a position calculated by the system's software, and it is formed by photo-curable resin solidification, filament material extrusion, ink-jet printing, laser fusion, lamination, etc. The process of building RP prototypes includes the following steps (known as process planning): determine the optimal build-up orientation, generate the support structures (if required), slice the 3D model, generate the scanning or the extrusion paths, and set the process parameters.

Some of the most important characteristics of RP processes, which influence their applications in robotics but also in other areas, are:

- Surface quality. The staircase effect, innate to layered fabrication, is mainly responsible for the surfaces quality of the prototypes. The type of RP process, the building material and the build-up orientation are influencing this aspect. The designer, when prescribing the roughness values, must know that, for instance, the surfaces oriented parallel or perpendicular on the building direction have the best quality (minimal staircase effect). It is also necessary to prescribe a roughness achievable by a layer by layer fabrication process, in particular by the process used for fabrication. Sometimes, in order to obtain a better surface quality, a post-processing operation is applied to the prototype (such as painting), but with negative effect on its accuracy.
- Accuracy. Each RP process/machine builds the prototype with accuracy dependent on a number of factors, among which the process parameters settings and the build-up orientation can be mentioned. Also, geometrical features of different dimensions and orientations are built with different accuracies. In these conditions, for each process, the fabrication accuracy must be known so that the designer to be sure that all the designed geometrical features will be built according with his/her specifications. Therefore it is important that this information to be available to his/her during the design process, in order to take the best decisions.
- Ability to build prototypes with very small/large dimensions.
- Mechanical characteristics. They are determined by the type of RP process and the construction materials, but also by the layer filling strategy. All these are influencing mechanical properties such as: tensile/compressive strength, impact strength, environmental resistance (humidity, temperature), time resistance, etc.
- Ability to build fine details depends on the RP process/machine. Very thin walls, small diameter holes, small radius blends, small dimensions chamfers are part of this category.
- Building orientation. As mentioned before, the building orientation influences many of the prototype characteristics, and sometimes finding the best orientation can be a complicated task (especially for prototypes with complex geometry). According to the chosen build-up orientation, the designer will know if certain geometrical features can be built or not, if they require support structures (with implications on the surface quality in contact with the support, on the post-processing, on the trapped volumes, etc.), and how the building cost/time will be affected. Hence, it will be highly important for the designer to know and analyze all these aspects, in order to take the best decisions.
- Support structures removal. In RP processes (e.g. FDM, SL) support structures are built to: sustain the overhang features; maintain prototype stability; sustain prototype slope walls; prevent building the prototype directly on the RP machine platform; prevent excessive shrinkage; sustain the floating components of a prototype. Support structures are eliminated at the end of the process and the part is post-processed. Supports influence the surface finish, build time and cost, all aspects with important roles in the RP application fields.

Build time/cost. Short building time and smaller costs are the foremost advantages of using RP comparing with the conventional methods for manufacturing prototypes. However, despite the common perception, build times in RP processes do not always depend on the part size. E.g. in SLS the process cycle contains mandatory warming and cooling stages which do not depend on the part size, thus being more efficient to build large parts than small ones. There are RP processes (SLS, FDM, etc.) which allow building simultaneously a group of prototypes, in this case the machine is used more efficiently and the cost per prototype is smaller.

3. RP APPLICATIONS IN ROBOTICS

The design of robotic mechanisms is a task that involves different types of analyses starting with geometry and kinematics, and including dynamic, tolerance and performance studies and specifications. Thus, the use of a physical prototype which materializes the mechanism would be beneficial for the designers in order to evaluate the characteristics and the problems posed by the proposed structure. In this respect, RP processes offer the solution to quickly manufacture a fully functional mechanism. Moreover, the possibility to produce parts with insertions or multi-materials parts will make easier to incorporate and attach sensors, actuators and transmission elements within the structure and joints of the mechanism [7, 18].

In robotics usually RP processes are used to [2]:

- visualize the whole mechanisms and each joint limits,
- evaluate the working space,

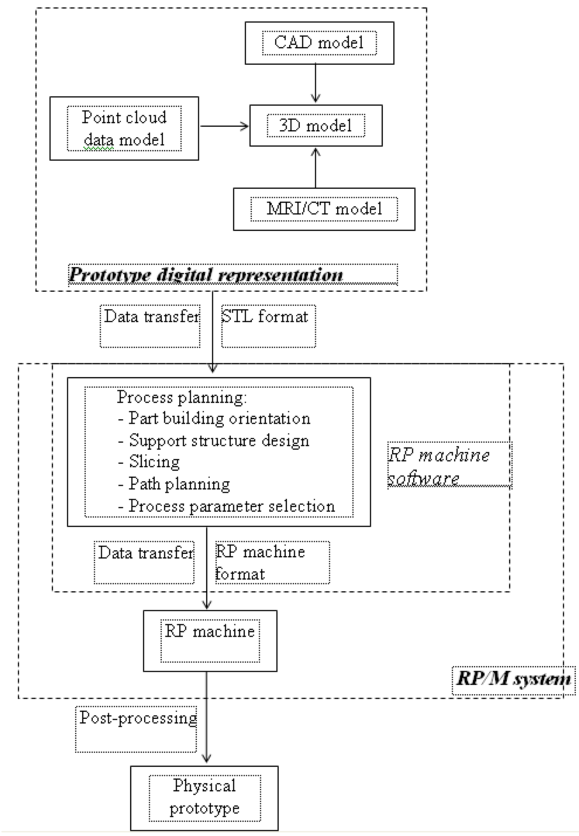


Fig. 1. RP process chain for building physical prototypes.

• determine the interferences between different links,

• identify the singular configurations including uncertain configurations where the mechanism has internal mobility.

Considering, as mentioned above, that the one of the actual trends in RP is the movement towards Rapid Manufacturing approach, this will allow also using RP processes in order to manufacture joints, jigs and fixtures needed for a robot. In addition RP allows obtaining multi- link mechanisms in one-step fabrication process, without requiring assembly of its structural members and joints after fabrication [6, 7]. The survey of the literature in the field shows that the RP applications in robotics can be divided in three broad categories [15]:

1. Manufacturing rigid links, as a straight-forward application for RP

2. Manufacturing joints in order to:

• visualize the whole mechanisms and each joint limits,

• evaluate the working space,

• determine the interferences between different links,

• identify the singular configurations including uncertain configurations where the mechanism has internal mobility.

In this case two situations can be considered: manufacturing joints in several parts and then assemble them, or manufacturing the joint directly assembled (special attention being paid to geometry gaps and clearances analysis and evaluation, and support structures removal).

3. Manufacturing parts for robots, with the possibility to build multi-material parts or parts with insertion.

One of the first reported papers in the field of designing mechanisms with the use of RP processes is [14] who used Fused Deposition Modeling process to build a six-legged six degree of freedom parallel manipulator from several parts and then assembled them together. This work was continued in [2], where the authors presented the fabrication in one part (without requiring assembly) of different types of joints (revolute, spherical and prismatic) and a 6DOF parallel manipulator on a SLA 190 system. All the joints were first design using I-DEAS 3D modeling software and then manufacture via stereolithography process.

The disadvantages mentioned by the authors [2], [5] at that time regarded: support structure removal, clearance accuracy and limited range of materials (Figs. 2 and 4).

SLA and SLS processes are used in [10] for manufacturing two types of robotic systems: a three-legged parallel manipulator and a four degree of freedom finger of a five-fingered robotic hand, both as non-assembly mechanisms (Fig. 3). SLA process was also analyzed in [20] for suitability in obtaining the optimal clearance for manufacturing non-assembly prismatic joints and revolute joints. Further [8] presented the fabrication of a very different type of compliant joints manufactured with SLA. In the Golem Project [16] studied the automatic design and manufacture of call “robotic life-forms” manufactured with 3D Printing. They programmed software to automatically design robots to move autonomously on a horizontal plane by utilizing evolutionary computation. The output of the software is a STL file for uses in any RP. The entire pre-assembled machine is printed as a single unit, with fine plastic supports connecting between moving parts, actuators and sensors were assembled to the robots [16] after fabrication (Fig. 5).

In [15] the authors presented the research experience of two research groups concerning the RP applications in mechanisms design and manufacture using FDM and SLA processes. An extensive analysis on advantages offered by RP technologies and the research works in this field are presented as well.

In the last couple of years, the research focused also on developing a technology for building parts with insertion (for instance, actuators and sensors), this way en-

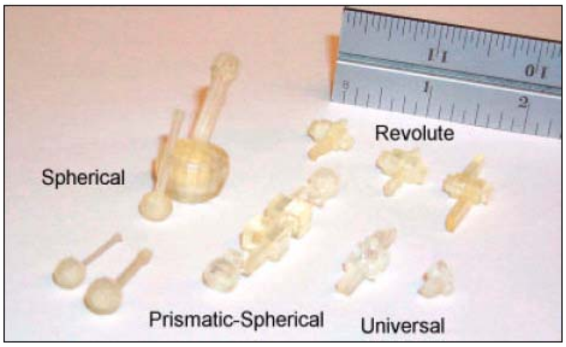


Fig. 2. Joints fabricated using stereolithography process.

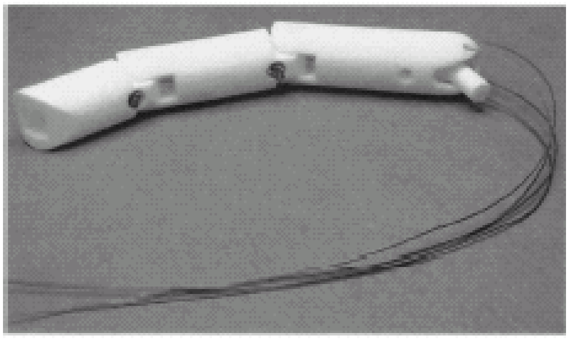


Fig. 3. Robotic finger manufacturing with SLS.

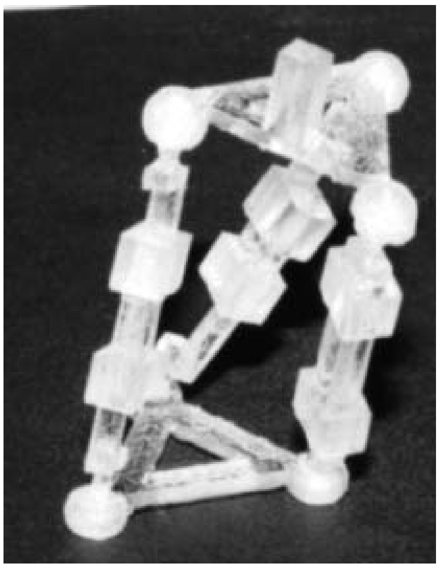


Fig. 4. Parallel manipulator configuration.

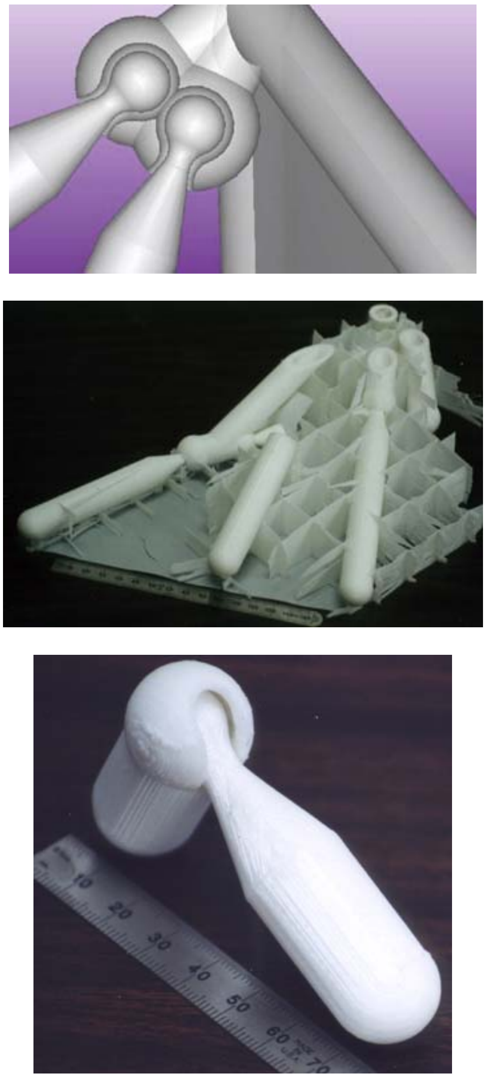


Fig. 5. Golem project, Automatic Design and Manufacture of Robotic Lifeforms via 3D Printing.

hancing the capabilities offered by SLA [20, 4]. This is an extension of the concept of "design by composition" introduced in [20], that refers to the design and fabrication of mechanical parts with embedded electronic, sensor, and actuator components. The highly integrated mechanisms that can be fabricated with the Shape Deposition Manufacturing (SDM) process and the design by composition approach can result in small robotic systems with increased performance and reliability, as the authors are emphasizing.

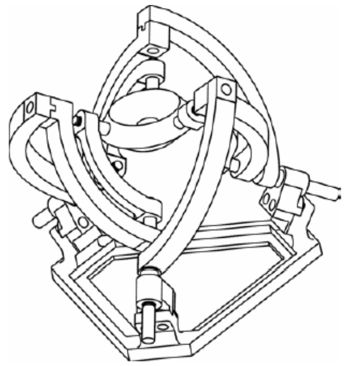
The use of SDM in manufacturing small robots with embedded sensors and actuators is studied in [3]. Moreover, the process planning associated with structures with spatially varying material properties is also considered.

SDM process offers the possibility to embed different components (sensors, actuators etc.) in the internal structure of the part, which recommend it for this type of applications.

The problems identified by [20] particularly regarded the support structures and recoating issues around inserts, the problems identified by a practical approach being used for improving the SLA process. The position of the inserts (horizontal, vertical and alignment) is considered for avoiding laser shadowing or recoating obstruction situations, but also their tolerance is analyzed depending on size, length of contact surface, type of joint, orientation, etc. The support structures removal can cause difficulties to the relative part motions and in order to avoid this appropriate part and inserts orientations must be considered.

Other issues of study in the multi-material assembly process for RP regards finding an optimal path plan for avoiding tools interferences when filling the 2D layers with different materials [11].

Another research presented in [17] is focused on how to integrate CAD/CAM/CAE and RP in the development of a humanoid biped robot. The body parts of the robot were designed in Pro/E software and the structural CAE analyses were performed with ANSYS 7. Also, motions analyses were conducted using Visual Nastran. Some of the robot's parts were built directly from on Eden330 machine and for others CAM traditional technologies were used. Also, This integrated approach allowed the researcher to decrease the humanoid robots weigh to 25.4 kg, while maintaining a compact body design, walking stability at 0.72 km/h and an accurate motion control.



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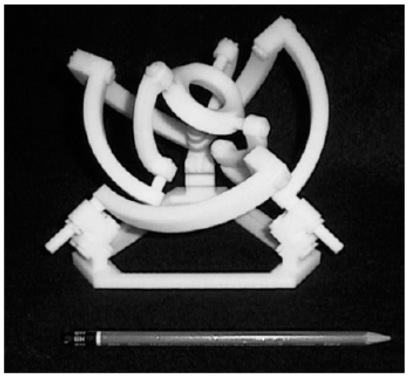

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Fig. 6. Agile eye, a - CAD model, b- RP model.

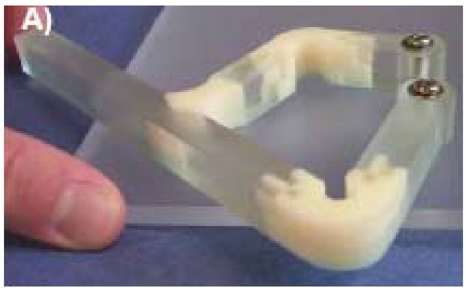

Fig. 7. Prototype with insertion manufactured using RP.

Fig. 8. RP model from ABS.

4. CONCLUSIONS AND DISCUSSION

Rapid Prototyping processes had proven to be efficient means to fabricate parts for different joints and structures composing robotic systems. The advantages offered in terms of cost, manufacturing time, capability to build complex geometrical shape directly from the 3D CAD model and also to build assemblies in one-step fabrication, recommends them for extensive use in robotics. The first challenging issues identified by the researchers in the field were: accuracy, clearance, support structures removal, possibility to manufacture parts in very small dimensions and limited range of materials. Currently there are RP processes available for fabricating very small parts (MicroTEC Germany), metal parts (EOS, MCP-HEK), or RP processes with water-soluble support structures, etc. Thus, the evolution in RP/M field solved some of these problems, but also opened new research directions and challenges with the appearance of prototypes with embedded sensors and actuators.

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