Study on multifunctional rapid prototyping manufacturing system

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Multi-functional rapid prototyping manufacturing system (M-RPMS) is an important potential developing field and tendency of RP technique. Application area of the M-RPMS has been discussed in this paper. It is believed that the M-RPMS has to be developed both for industrial and academic purposes. The openness of software and hardware, the diversity of RP processes and the highest function/cost ratio are the outstanding speciality of the M-RPMS. This paper also introduces the design principle of the M-RPMS, the calculation method for function integration degree (FID), the running of SLS in the M-RPMS and the key of early stage rapid feedback design system.

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1. Introduction

Rapid prototyping (RP) is a rapidly developing technology. Its application covers all industrial and academic fields. However, these industrial and academic requirements are different: the industrial customers need high efficiency, fine accuracy and sufficient working space while the latter emphasizes software openness, technical diversity and recombination ability in system structure with acceptable efficiency, suitable accuracy and proper working space.

How to unify and harmonize these two requirements is an important problem. According to design and manufacturing of the multi-functional RP machine, it is the best way probably that one RP system possesses two or three kinds of RP technologies. The rapid protoyping manufacturing system (M-RPMS) (Yan *et al.*, 1996) in our laboratory is a special RP machine: it emphasizes the RP processes diversity, so it is suitable for academic field; it has a large working space, high efficiency and fine accuracy, so it is also a good machine both for universities and companies.

1.1 Openness of RP software

Openness of RP software means that the customers may select some of the provided function modules and integrate them with their self-developed modules freely. A set of new software, which has the required functions and features by the customer, is formed in the provided overall framework in the M-RPMS. It is necessary to open the following for customers in order to achieve the above requirements:

- main data structures;
- detail analysis of function requirement;
- major information transmission;
- data flow and overall software structure.

Apparently, all commercialized RP systems cannot reach these demands up to now. But these functions and features have been achieved in the M-RPMS. Figure 1 shows the data process modules of the M-RPMS.

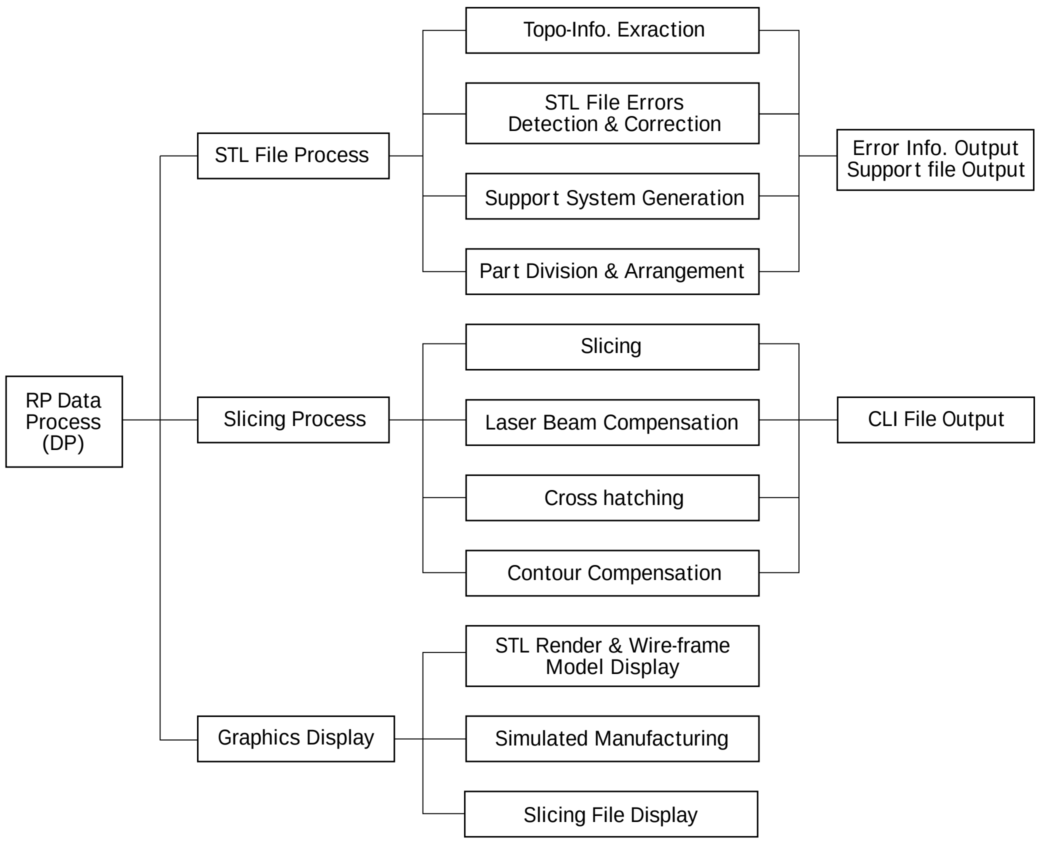
1.2 Processes diversity

There are more than 30 kinds of RP technologies, at the mature or the developing stages (Anon, 1996). The M-RPMS should provide several RP processes according to customers' interests, one or two of which should reach the present commercialized level.

There is the ability of recombination in structure in the M-RPMS. Based on analysis of modern forming science (MFS), RP technology belongs to discretization/stacking type of forming (Yan *et al.*, 1994). The discretization means to slice the 3-D CAD model in order to obtain the stacking paths and restrictions of materials. This process is accomplished by RP software, while material stacking is accomplished by machinery structure and control system. Recombination ability of structure is referred to provide a kind of flexible setting, which can be recombined by customers on both machinery structure and control system in order to achieve their specific requirement of new RP process development. Reasonable overall system structure is the basic assurance to realize the above requirement. According to the principle of dicretization/stacking forming, any RP process has two basic requirements (Yan *et al.*, 1997; Zhang, 1997).

1 To generate scanning routes and restrictions used to control material stacking through CAD model discretization. This is a data treatment process, which has no

Figure 1
Structure of DP function module

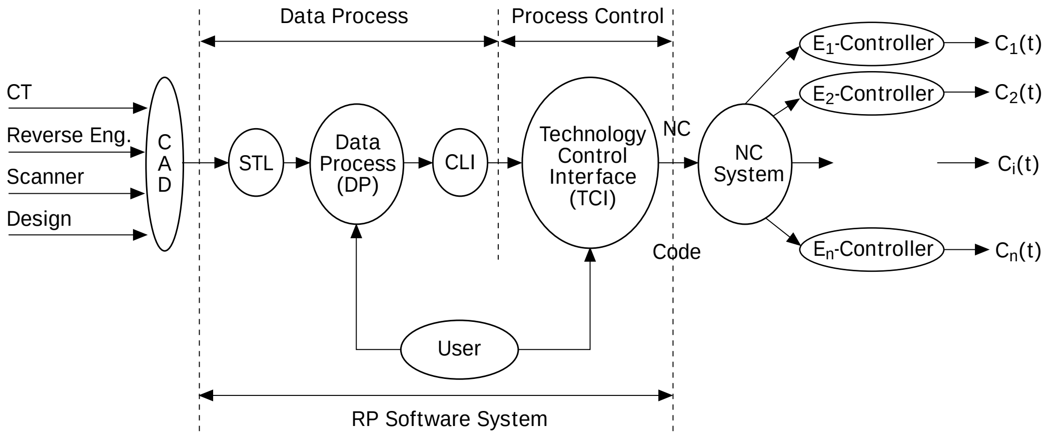


direct relationship with particular RP process and NC system. Its input is STL file while its output is CLI file (see Figure 2).

2 To generate NC Code according to the CLI file, particular RP process and NC system. Then NC system generates a series of control signals which can be used to control every working unit of RP system.

In Figure 2, customers may get involved in data process (DP) selecting and recombining certain functional modules in order to obtain new data process function. For very particular process rules and demands, customers'

Figure 2
Overall structure of RP software system



requirements may be involved in the M-RPMS through technology control interface (TCI).

2. Design principle of M-RPMS

The function integration (FI) is the principle for the M-RPMS design. At first, we have to analyze the RP technologies which will be integrated into the M-RPMS and then calculate the "integration degree", finally, arriving at a decision, the M-RPMS will consist of what kinds of RP technologies.

2.1 Analyses of RP technology

Table I shows a sample of RPM process ability matrix (Du *et al.*, 1997). Here only four techniques have been listed, including stereolithography (SLA), laminated object manufacturing (LOM), selective laser sintering (SLS) and fused deposition model (FDM). The items (i.e. material, dimensional tolerance, surface finish, matching cost and time) are specified to determined the ability of each process.

Apparently, SL technology has the best roughness, but the synthesis cost and material cost are the highest in all of them. Every RP technology has its own merits and weakness, we can not say which kind of RP technology is the best. Integration of different RP technologies in one machine is the best method.

2.2 The principle of function integration

A typical multi-functional RP machine consists of basis functions and special functions, it can be seen in Figure 3.

The "basis" could also be shared by any new RP technology (marked by *new* in Figure 3) if it is hoped to be integrated.

2.3 The integratibility of RPM subfunctions

The final purpose of RPM is to accomplish the material stacking according to the differentiated geometry data of prototypes/parts. These functions served for the final purpose are called subfunctions. Above basis function is so called subfunction.

For example, the "basis" system in M-RPMS which consists of many subfunctions, can be shared in a higher degree, i.e. it can be shared by more RP processes, then they are more deserved and more rational to be integrated together.

Integration degree matrix is a kind of design matrix (Steward, 1981; Yan *et al.*, 1996). It is a tool for calculating integration degree (see Table II).

The first line in the matrix stands RP processes technology P_1, P_2 ... which are possessed of the M-RPMS. The F_1 is shared by P_1, P_2 and P_3 so the its value $P = (3 + 3 + 3)/3^2 = 9/9$. The F_2 is only shared by P_1 and P_3, although P_2 needs F_2 ,but it cannot apply directly. So, at second line, the matrix's

Table I
RPM process ability matrix

Kind of process	Kind of material	Process tolerance	Roughness Ra(μm)	Machining cost Synthesis cost	Machining cost Material cost	Machining time Scanning speed	Post-process
SL	Resin	IT15	3.7/1.7	\$20.0/h	\$150/kg	500-5,000mm/s	1-2days
LOM	Paper	IT16	4.0/2.4	\$7.5/h	\$40/kg	280mm/s	
SLS	Ceramic Plastic Alloy	IT14	16/15	\$20.0/h	\$100/kg	1,061-2,000mm/s	1-2 days
FDM	Plastic	IT15	11/5.0	\$12.8/h	\$100/kg	380mm/s	

Notes:
1 Machining tolerance value can be converted from international tolerance degree (ITD) into dimensional tolerance with checking the ISO standard
2 Surface roughness is varied with the influence of shaping direction (⇒/⇑). An average value can be adopted for each RP technology
3 When calculating the machining cost, three main procedures including preprocessing, part building and post-processing should be considered. Here in order to simplify the computation, a synthesis cost per hour is introduced. So the overall machining cost can be determined by the following equation:
Cost = synthesis cost × time + material cost × part weight
4 Machining time equals to the sum of time spent on the two procedures: part building and post-processing. The gross time for building a prototype can be calculated by the following equation:
Building time = volume/(layer thickness × distance between scanning steps × scanning speed)
5 For SLA, FDM, SLS cases, the "volume" in the above equation means the volume of the prototype needed to be built. It can be easily calculated with CAD software or from STL file. For LOM process, the "volume" means the frame volume with subtracting the prototype volume

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Figure 3
Schematic of a typical multi-functional RP machine

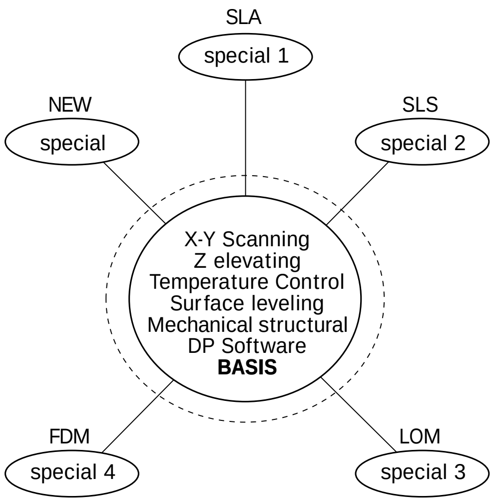


Table II
Integration degree matrix

RP process	P_1	P_2	P_3	P
Function				
F1	3	3	3	9/9
F2	2	1	2	5/9
F3	0	2	2	4/9
F4	0	0	1	1/9
F5	1	1	1	3/9
F	6/9	7/9	9/9	22/9

elements are 2, 1 and 2 respectively and the value $P = (2 + 1 + 2)/3^2 = 5/9$. In the third line P_1 does not need F_3, so their elements equal zero, but two RP processes P_2 and P_3 require F_3, so the elements equal 2. For F_4 only one RP process P_3 demands it so the element equals 1. Although each RP process needs F_5, but they are different and can not be shared, so their elements equal 1. The total P equals 22/9. Similarly, the total F is equal 22/9 too. Because there are five functions ($F_1 \ldots F_5$) in the matrix, so the integration degree I equals

$$I = 22/9/5 = 0.488.$$

For a M-RPMS, which possesses m_0 subfunction and accomplishes n_0 RP processes. The matrix element is P_i, then the I is

$$I = \frac{\sum_{j=1}^{m_0}(\sum_{i=1}^{n_0} P_i)_j}{n_0^2 \times m_0}$$

If three RP processes are chosen from SLA, LOM, FDM and SLS, while there are 15 subfunctions. Then the value of I is

I = 0.547 for LOM + FDM + SLS
I = 0.415 for LOM + FDM + SLA
I = 0.422 for SLA + FDM + SLS

3. Case Study

3.1. SLS running in the M-RPMS

The basis function of the M-RPMS can be used for SLS directly (Zhang *et al.*, 1996; Zhang *et al.*, 1997) only the powder feeding, powder spreading and powder pressing has some special structures. In fact, the pressing foil, heating sheet function for LOM can be designed again if SLS is integrated into the M-RPMS. The multi-functional roller is of use for powder feeding, spreading and pressing and sheet pressing and heating both for SLS and LOM.

The powder hopper is a special functional element (see Figure 4).

The hopper has an on-off element which can be controlled by the software to feed a fixed amount of powder or shut down the hopper in the right process.

In the M-RPMS, hot pressing and powder sending system can be seen in Figure 5.

3.2 The M-RPMS as the key of the ESRFD

Early stage rapid feedback design (ESRFD) (Bullinger *et al.*, 1995; Lu *et al.*, 1997; Suh, 1990) is a kind if new design method based on RP technology. Design iteration is the main feature of the design process, this iteration can not be avoided. Design iteration is the repeat of design tasks because of the appearance of new information. One reason is that error or unsatisfaction may be found in down

Figure 4
The hopper

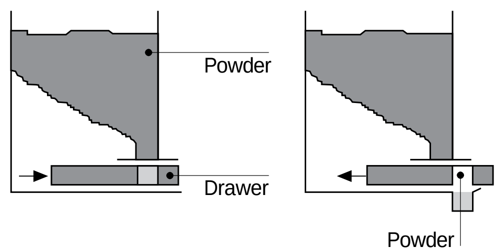
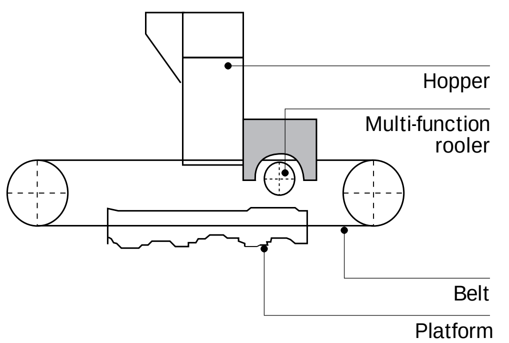


Figure 5
Multi-functional roller and hopper



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stage design tasks. Thus the up stage design tasks are repeated to solve this problem. Another reason is that the up stage has some problems or the design is changed, then the down stage design needs repeated. All these iterations could be found in many cycles in machinery design process.

In traditional design method, design iteration often appears in the late stage of the design. It causes many cycles in design and affects the design cost and time greatly. Especially the increase of development time impairs the competitiveness of the new product significantly.

Figure 6
Real ESRFD (*TDS is a 3D reconstruction method from 2D photograph)

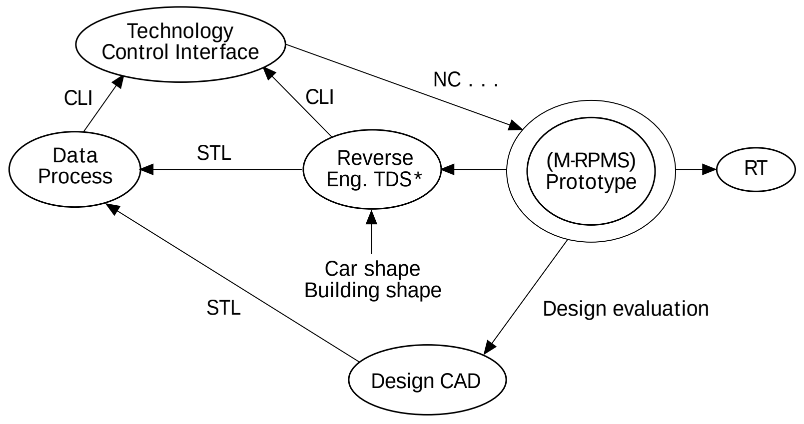
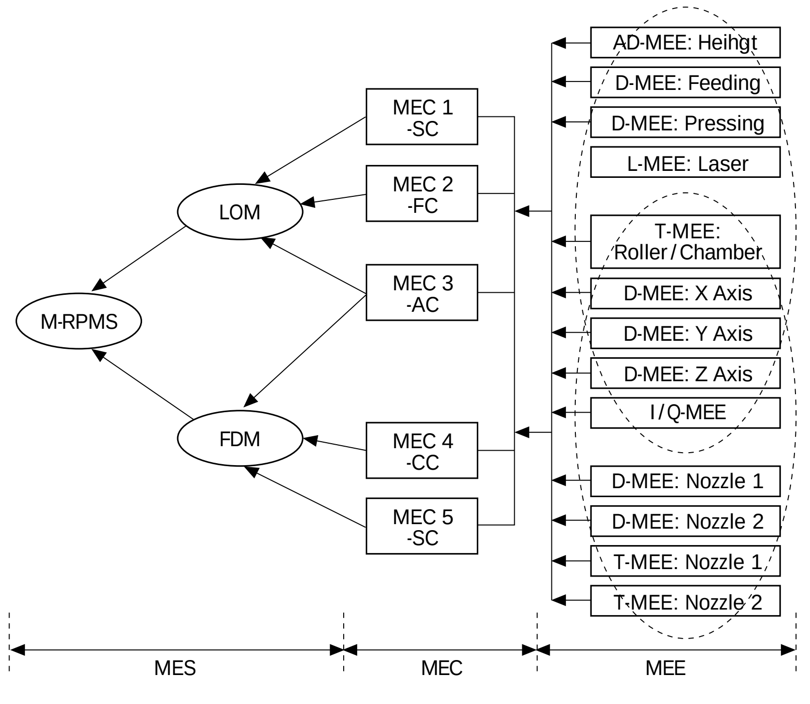


Figure 7
M-RPMS-II function integration scheme



In this situation, the key is how to find problems in early stage design and to complete the design iteration as early as possible. This so-called early stage rapid feedback design (ESRFD).

ESRFD has to be supported by rapid prototyping, virtual prototyping and simulation technique, etc. Especially, the supporting of rapid prototyping technology is more important.

The M-RPMS is easy to satisfy different requirements from concept design on early stage design. Usually we need several kinds of physical mould to evaluate the design, single function RP machines is difficult to supply this service. This is one of the reason in many RP service offices that two or three RP machines are installed. This will result in investment increasing and machine idle.

Apparently, the M-RPMS supplying two or three kinds of prototyping is most suitable for ESRFD. Figure 6 shows the system structure of real ESRFD in Center of Laser Rapid Forming, Department of Mechanical Engineering, Tsinghua University, China.

3.3M-RPMS-II

M-RPMS-II developed by Center of Laser Rapid Forming, Department of Mechanical Engineering, Tsinghua University has two RP processes with large working space:

1 For LOM, the prototype size is 600 × 400 × 500mm.
2 For FDM, the prototype size is 500 × 400 × 500mm.

Its function integration scheme can be seen in Figure 7.

In Figure 7 MES – mechanical electronics system; MEC – mechanical electronics component; MEE – mechanical electronics element.

4. Conclusion

1 Multi-functional RP system is an important potential developing field and tendency of RP.
2 The M-RPMS is suitable both for industrial and academic fields.
3 The outstanding specialty of the M-RPMS is software and hardware openness, RP processes diversity and the highest function/cost ratio.
4 The calculation of function integration degree is important for the M-RPMS design.
5 The M-RPMS is the key of early stage rapid feedback design system.

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