Development of a Computer Aided Process Planning System for Prismatic Parts in Hybrid Manufacturing

Osama Abdulhameed
Industrial Engineering Department
College of Engineering, King Saud University
Riyadh, Saudi Arabia
Princess Fatima Alnijiris's Research Chair for Advanced Manufacturing Technology
(FARCAMT Chair), Advanced Manufacturing Institute, King Saud University, Saudi Arabia,
osamaie@gmail.com

Abdulrahman Al-Ahmari
Industrial Engineering Department
College of Engineering, King Saud University
Riyadh, Saudi Arabia
Princess Fatima Alnijiris's Research Chair for Advanced Manufacturing Technology
(FARCAMT Chair), Advanced Manufacturing Institute, King Saud University, Saudi Arabia,
alahmari@ksu.edu.sa

Mohamed Abd Elhamid
Advanced Manufacturing Institute, King Saud University, Saudi Arabia

Abstract

Nowadays, the development of manufacturing industries still relies heavily on research into manufacturing processes and materials and the development of new products. In addition to the traditional competition requirements for low cost and high quality, the competition pressure for today's manufacturing industries are more complex products, shorter product life cycle, shorter delivery time, more customized products and fewer skilled workers. Today's products are becoming much more complex and difficult to design. Tow fundamental manufacturing processes have been used Subtractive manufacturing (SM) and Additive Manufacturing (AM). SM is the process of cutting material from a block to produce designed part from 3-D, 2-D model or G-Code. The introduction of 3-D complex surface modeling software programs took the place of writing codes. Unlike CNC machines of the 1940s, today's CNC machines are highly automated using CAD/CAM programs. AM is defined as the process of joining materials by either fusing, binding or solidifying materials such as liquid resin and powders usually layer upon layer to produce an object from 3-D model data. Terms such as 3-D printing, rapid prototyping, direct digital manufacturing, rapid manufacturing and solid freeform fabrication are often used to describe AM processes. AM processes are driven by 3-D computer data, or stereo-lithography (STL) files, which contain information on the geometry of the object. Additive Manufacturing is efficient for low volumes production, high design complexity and frequent changes. Hybrid manufacturing processes are carried out in either parallel or serial manner with the objective of enhancing their advantages whilst minimize their disadvantages. The hybrid manufacturing processes satisfied significant improvement in tool life, material removal rate, dimensional and geometric accuracy, and reducing production times. Absence of proper Computer Aided Process Planning systems (CAPP) restrict utilizing additive/subtractive manufacturing in many industrial applications due to the complexly in designing systems inputs from the design phase. Therefore, this thesis aims to develop a CAPP system for additive/subtractive manufacturing for prismatic parts.

Keywords
Additive manufacturing, Subtractive manufacturing, Inspection process, Hybrid process, Process planning

1. Introduction

The trend in manufacturing are the producing very complex part without any assembley by comining a lot of individual process as a hybrid processes. The combinations of additive/subtractive processes has have been gradually used to meet the challenges in the reduction of tool wear and production time and the increase of machining effectiveness with tight tolerances and high levels of surface finish. AM parts usually possess a poor surface quality, therefore, they are machined to produce smooth surface finish. AM process can be integrated with SM process to produce the finely-finished parts. Largely, CNC milling is the most common procedure to machine the near-net shapes obtained from AM [1].

2. Literature Review

This research contributed significantly to the hybrid methods and their process planning. however, there is a lack of research focusing on the development of optimization methods for process planning of hybrid additive and subtractive manufacturing process. there is always a requirement to develop an optimized capp system for hybrid process that can adapt to changing machining conditions. therefore, in this work, an optimized capp has been proposed to fabricate parts in shortest time using the hybrid additive, subtractive and inspection processes. the mathematical models have been developed to optimize part orientation as well as minimize additive and subtractive times. besides, genetic algorithm (GA) has been employed to obtain the best path with minimum inspection time [2]. While subtractive method is the only option when it comes to high quality components, but it a slow and costly route. On the other hand, additive method is building the design in to the physical objects without any human intervention. But its low in surface quality. The combining CNC machining processes with additive processes may provide new solutions to the limitations of additive processes due to the high accuracy, improved quality and speed that machining processes offer. Karuna karan, et al, [3] presented a hybrid layered manufacturing process to combine AM and to an existing CNC machine for making metallic objects without disturbing its original functionalities. An introduction of a novel hybrid process combining additive, subtractive and inspection processes in a serial manner presented by [2]. A combination of additive, subtractive and inspection, entitled iAtractive, is proposed for getting process plan sequences as a hybrid process [3]. The process planning methods capable of effectively utilizing manufacturing resources for hybrid processes are currently limited. The case study demonstrated the efficacy of the proposed process planning algorithm and indicates that the iAtractive process has better flexibility and capability as compared to individual additive and subtractive processes. Process planning is the decision-making process for determining methods to manufacture a part according to its design specification and the selection of parameters and necessary production processes in order to transform raw material into a part. A process plan specifies the machines, setups, tool specifications, etc. required to convert raw material into a finished part. In effective process planning and scheduling, the tradeoff among cost, time and quality should be taken into consideration. Afsharizand, et al, [4] proposed a decision-making model for manufacturing technologies which are becoming increasingly complex due to on-going rapid developments in additive and subtractive (Addtractive) manufacturing. This decision-making in manufacturing technologies should be based on machine and resource capabilities. In this research, a formal modeling approach is proposed to facilitate modeling of machining capability and associated Addtractive operations. This mathematically based formal method allows system properties to be described in a well-defined manner. The ISO-standardized Z notation (named after Zermelo-Fraenkel settheory) has been utilized to build a state-oriented formalism model for machining capabilities and associated operations. Liou et al. [5] and Zhang and Liou [6] incorporated a laser cladding unit with a five-axis milling machine.

3. Research Methodology

The combinations of additive/subtractive processes has have been gradually used to meet the challenges in the reduction of tool wear and production time and the increase of machining effectiveness with tight tolerances and high levels of surface finish. The framework demonstrated in Figure 1 shows explicitly generic overview of the proposed integrated system. The proposed system is capable of automating the selection of critical and functional Cartesian point on the design from CAD database. This ability predicts process planning scenarios and calculating the best scenario.

3.1 Automatic feature extraction and recognition

The first part of the proposed methodology consists of the automatic feature extraction and recognition from CAD solid systems used for CAD and CAM integration. The CAD files contain detailed geometric information of a part, some of which are not suitable for using in the downstream applications like process planning and inspection. The different CAD or geometric modeling packages store the information related to the design in their own databases. The structures of these databases are different from each other. As a result, no general or standard structure has been developed so far, that can be used by all CAD packages. For this reason, this thesis proposes an intelligent standardized feature recognition methodology to develop a feature recognition system that has the ability to communicate with various CAD/CAM systems. The system takes as input, Standard for the Exchange of Product data (STEP), and translates the information in these file into manufacturing information, which provides process plan. The feature recognition algorithms are able to recognize slots (through, blind, and round corners), pockets (through, blind, and round corners), holes (blind and through), and steps (through, blind, and round corners). The proposed methodology can also handle the interaction between the different features. These features, called as manufacturing information, are mapped to the process planning function as an application for CAM. The system is written in the C++ language on a PC-based system.

Extracted manufacturing features in terms of feature identification number (ID), feature name, feature dimensions, and feature's location relative to the original coordinates of the deigned part have been shown in Table 1.

Table 1: Feature Recognition

Feature Id	Feature Name	Face Ids	Feature Dimension	Feature Volume
1	Two Slot Through At Two Level	1,5,4,8,11,6,9, 7,10	Lenght1: 140 Width1: 40 Height1: 30 Lenght2: 40 Width2: 20 Height2: 20 Lenght3: 40 Width3: 20 Height3: 20	200000
2	Two Slot Through At Two Level	2,13,12,19,16, 17,14,18,15	Lenght1: 140 Width1: 40 Height1: 30 Lenght2: 40 Width2: 20 Height2: 20 Lenght3: 40 Width3: 20 Height3: 20	200000
3	Pocket Through	46,48,49,47	Lenght: 20 Width: 30 Height: 140	84000
4	Slot Through	57,56,58	Lenght: 110 Width: 20 Height: 10	22000
5	Slot Through	60,59,61	Lenght: 110 Width: 20 Height: 10	22000
6	Pocket Blind	66,67,65,63,64	Lenght: 50 Width: 20 Height: 10	10000

3.2 Process Planning

Process planning generates a description that specifies contents and sequences of operations. The results consist of the subpart information which depends on Cartesian point to check between build and machining process or together. In additive/subtractive processes, automatic generation of process planning is crucial due to the features cartesian point in vertical direction. These tasks include determining of all scenarios using the best strategies for given vertical surfaces, and generating the total cost of the best scenario. Basic planning steps involve determining the part orientation, extracting the Cartesian point, Part Scenario, determining build sequence and direction for subparts and checking the feasibility of the machining process.

3.2.1 Part Orientation

The determination of the base face from which the building process of the part starts is very important. The setup planning of the prismatic parts algorithm will be dependent in Probe accessibility direction which is an important factor in determining all setups needed to cover all features. The probe accessibility direction of a feature is an unobstructed path that a probe can take to access the feature. Features with the same probe accessibility direction can be grouped into one setup. A feature may have more than one probe accessibility direction and hence can be grouped into different setups. The probe accessibility represents the accessibility direction of the probe as shown in Figure 2 to measure the feature.

In the setup planning, the grouping of the features depends on PAD as input in order to (i) determine the common of preferential base for allocating the part which allow the probe to access at least all features (ii) clustering of features based on the common preferential base (iii) Filtering of multiple occurrences of the features in different clusters. The preferential base of a feature is defined as primary locating face on which the probe has to inspect at least all features. By using feature data extraction and recognition as an input some rules are built to allocate preferential base for inspecting the features and some of them have more than one preferential base.

The case contains thirteen features as shown in Figure 3. All features can be inspected by keeping any of the possible faces ID as base which are arrange in ascending order frequency: f(47,48), f(53,91), f34, f92, f27, or f52, as shown in Figure 3. Then the best bottom face which contains less interaction edges frequency is face ID (47, 48), at (1, 0, 0) normal vector.

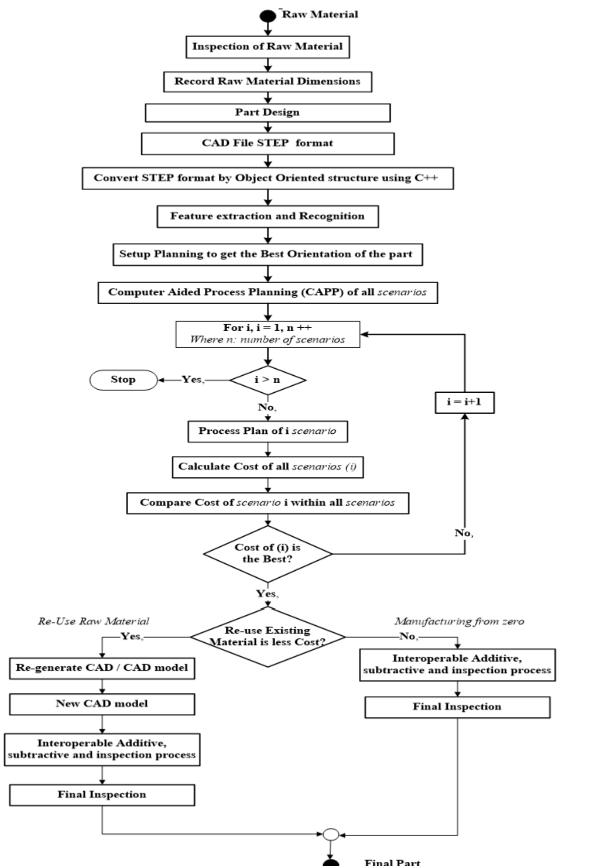


Fig. 1: Generic overview of the proposed integrated

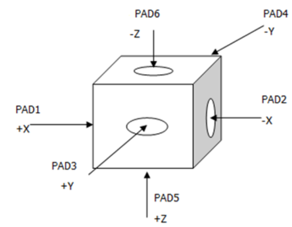


Fig. 2: Probe Approach Direction (PAD)

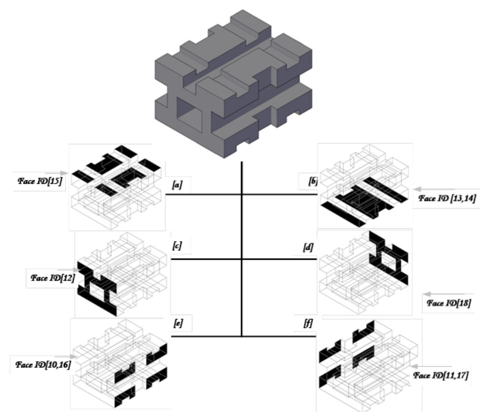
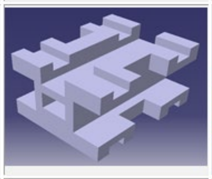
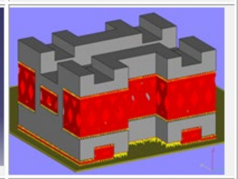
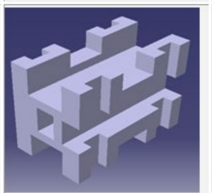
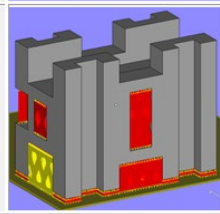
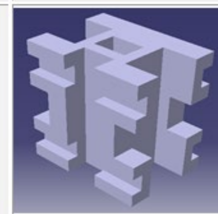
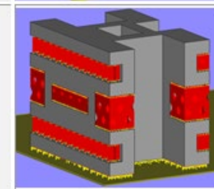
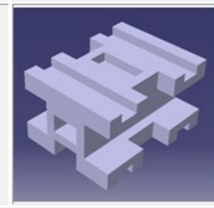
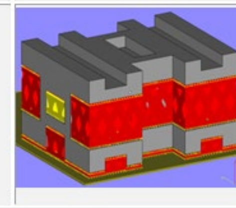


Fig. 3: The possibility of bottom faces

The comparison between the best possible setup orientations and the others setup orientation is shown in Table 2. This validation satisfied the orientation selection to a voiding increasing support material in the additive operation.

Table 2: The comparison between the best left face within the others faces:

Setup No.	Part Orientation	Support Structure
1		
2		
3		
4		

3.2.2 Process Planning Scenario

The part is divided into a set of subparts, depends on the feature Cartesian point which can be deposited and machined. Each branch of the Cartesian point corresponds to a subpart.

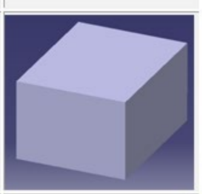
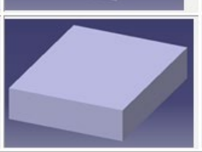
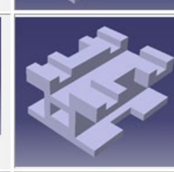
To find the best scenarios, it should consider both the machining time and the deposition time as follows:

$Td(n)\ \alpha\ N1,\ Tm\ (n)\ \alpha\ Vm$

Where: Td(n) is the deposition time, Tm(n) the machining time, Nl the number of layers, Vm the machining volume

To facilitate additive/subtractive scenarios, it is preferred that a part has many vertical surfaces (Cartesian Point) with respect to the building direction. The all possible scenarios are shown Table 3:

Table 3: The possible scenarios

Scenario No.	Raw Material	Subtractive	Additive
1			
2			
3			
4			
5			
6			
7			

To calculate total cost for every scenario, various weighted values are added to find the best scenario which has the minimum cost. The formula is as follows [1] as shown in Table 4 and Table 5:

$$Cost = CR\ WR + Ca\ Ta(n) + Cm\ Tm(n) + Cb\ Vb + Cs\ Vs$$

Where:

CR : Cost of raw material per Kilogram

WR: weight of raw material

Ca: Cost value of additive time,
Ta(n): additive time,
Cm: Cost value of machining time,
Tm(n): machining time,
Cb: Cost value of bridge,
Vb(n): Volume of bridges
Cs: Cost value of support structure,
Vs(n): Volume of the supports
n: the number of feature

The formulation cost will be applied for the second scenario as following:

Cost = CR WR + Ca Ta(n) + Cm Tm(n) + Cb Vb + Cs Vs

Where:

CR : Cost of Ti6Al4V alloy per Kilogram equal to (396 $/ kilogram)

To calculate the WR in kilogram where volume of raw material = 616 cm^3 and the density of the Ti6Al4V alloy one cubic centimeter contains 3.8 gram.

WR in kilogram = [(616 X 3.8) / (1000)] = 2.3408 kilogram

Ca: Cost value of additive time coming by experience = 266.67 $ / hr

In additive manufacturing process of Ti6Al4V alloy, 90 microns depth of layer needs 30 seconds. Therefore, 10000 microns depth needs in hours = (10*0.00833/0.09) = 0.9256 hours.

Ta(n): additive time = 0.9256 hours.

Cm: Cost value of machining time coming by experience = 106.67 $ / hr.

In subtractive manufacturing process of Ti6Al4V alloy s, material removal rate of 193 cubic centimeter needs 15 minutes [ ]. Therefore, 169230 cubic millimeter needs in hours (169230*0.0167)/12866.67 = 0.2197 hours.

Tm(n): machining time = 0.2197 hours.,

Cb: Cost value of bridge = 396 $/ kilogram, Vb(n): Volume of bridges = 0

Cs: Cost value of support structure = = 396 $/ kilogram

Vs(n): Volume of the supports = 0, n: the number of feature = 8 features

Table 4: Cost details of all possible scenarios

Scenario No.	subtractive Volume (mm^3)	Additive Volume (mm^3)	Raw Material Volume (mm^3)	Support Volume (mm^3)	Raw Material cost ($)	Raw Material cost Additive ($)
1	538000	-------	1232000	0	1853.9	-------
2	456000	72000	1078000	0	1622.2	108.34
3	398000	168000	924000	0	1390.4	252.81
4	96000	328000	462000	0	695.22	493.6
5	86000	472000	308000	0	463.48	710.26
6	------	694000	-------	140000	-------	1044.3

Table 5: Cost details of all possible scenarios

Subtractive Time (hr)	Time cost of subtractive ($)	Additive Time (hr)	Time cost of Additive ($)	Total Time (hr)	Total cost of ($)
1.697	191.002	0	0	0.697	2044.9
0.591	63.005	0.926	246.91	1.517	2040.4
0.516	54.991	1.852	493.83	2.368	2192.1
0.124	13.264	4.63	1234.56	4.754	2436.6
0.111	11.883	5.556	1481.48	5.667	2667.1
--------	0	4.41	1975.31	7.407	3019.6

3.2.3 Manufacturing Sequence

This stage of the methodology is constituted by the comparison of the scenarios obtained in stage 2 in order to choose the best scenario which has the minimum cost. The comparison is done directly between these costs of scenarios calculated in the first one-piece CAD model and the best scenario will be selected as the final process plan of the CAD model. The results are presented in Table 4.

3.2.4 Machinability Check

The main purpose of machinability check is to choose an optimal building sequence. If any kind of collision happens or an undercut plane appears, the corresponding sequence will be discarded.

3.2.5 Process Planning Constraints

There are several constraints for process planning that result in a process switch; they are collision constraint, physical machine constraint, and continuity broken constraint. Finally, the best scenario which has the lowest cost is the second scenario including additive/subtractive process planning.

4. Conclusion

The selection of appropriate methods such as additive, subtractive or additive/subtractive techniques can help to meet following manufacturing challenges effectively:

- Reduction of tool wear
- Reduction of production time
- Increase machining effectiveness
- Improved accuracy with tight tolerances
- Achieving high surface quality

From present study, it can be concluded that two of the major manufacturing goals are most often in opposition such as reduction of time and cost; and improvement of quality and flexibility.

In this project, methodology has been presented and successfully implemented to select suitable manufacturing process such as additive, subtractive or additive/subtractive for given part design. To validate and test proposed algorithms, case studies have also been presented. It can be suggested from case studies that proposed algorithms are efficient and can be employed to determine which manufacturing method should be used for given design.

6. References

[1] Abdulhameed, Osama, et al. "Additive manufacturing: Challenges, trends, and applications." Advances in Mechanical Engineering 11.2 (2019): 1687814018822880.

[2] Zhu, Z., et al. "A review of hybrid manufacturing processes–state of the art and future perspectives." International Journal of Computer Integrated Manufacturing 26.7 (2013): 596-615.

[3] Karunakaran, K., et al., Low cost integration of additive and subtractive processes for hybrid layered manufacturing. Robotics and Computer-Integrated Manufacturing, 2010. 26(5): p. 490-499.

[4] Behnood Afsharizand, Aydin Nassehi, Vimal Dhokia, and Stephen T. Newman, “Formal Modelling of Process Planning in Combined Additive and Subtractive Manufacturing”, M.F. Zaeh (ed.), 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2013), Munich, Germany 2013

[5] Liou F, Choi J, Landers R, Janardhan V, Balakrishnan S, Agarwal S., "Research and development of a hybrid rapid manufacturing process", In Proceedings of the Twelfth Annual Solid Freeform Fabrication Symposium 2001, Austin, USA, (2001), p. 138–45.

[6] Zhang J, Liou F., "Adaptive slicing for a multi-axis laser aided manufacturing process", Journal of Mechanical Design 2004; 126 (March) P:254–61.

Biographies

Osama Abdulhameed is a Researcher and PhD Student in Industrial Engineering Department, College of Engineering, King Saud University, Saudi Arabia. He received his M.S (Manufacturing Systems Engineering) in 2014 from King Saud University. His research interests are in quality, inspection of manufacturing product, additive manufacturing; CAD /CAM and product, design analysis and design of manufacturing systems; optimization of manufacturing processes.
.

Abdulrahman Al-Ahmari is a professor in industrial engineering department at King Saud University He was the Dean of Advanced Manufacturing Institute (2012-2017), Executive Director of Center of Excellence for Research in Engineering Materials (2008-2012), Supervisor of Princess Fatimah Alnijris's Research Chair for Advanced Manufacturing Technology, and Supervisor of CMTT (Center of Manufacturing Technology Transfer). Also he was Chairman of Industrial Engineering Department at King Saud University (2004-2008). He received his PhD (Manufacturing Systems Engineering) in 1998 from University of Sheffield, UK. His research interests are in analysis and design of manufacturing systems; computer integrated manufacturing; optimization of manufacturing operations; applications of simulation optimization; FMS and cellular manufacturing systems.

Mohamed Abd Elhamid is an engineer in Advanced Manufacturing Institute, King Saud University, Saudi Arabia. His research interests are in quality, inspection of manufacturing product, additive manufacturing; CAD /CAM and product, design analysis and design of manufacturing systems; optimization of manufacturing processes.