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Technical paper

The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process

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ABSTRACT

The application of state of the art manufacturing processes has always been constrained by the capabilities either from technical limitations such as limited materials and complex part geometries or production costs. As a result, hybrid manufacturing processes – where varied manufacturing operations are carried out – are emerging as a potential evolution for current manufacturing technologies. However, process planning methods capable of effectively utilising manufacturing resources for hybrid processes are currently limited. In this paper, a hybrid process, entitled iAtractive, combining additive, subtractive and inspection processes, along with part specific process planning is proposed. The iAtractive process aims to accurately manufacture complex geometries without being constrained by the capability of individual additive and subtractive processes. This process planning algorithm enables a part to be manufactured taking into consideration, process capabilities, production time and material consumption. This approach is also adapted for the remanufacture of existing parts. Four test parts have been manufactured from zero and existing parts, demonstrating the efficacy of the proposed hybrid process and the process planning algorithm.

1. Introduction

Manufacturing technology has gone through a number of evolutionary developments over the past decades [1]. However, due to the technological constraints of individual manufacturing processes, it is not always feasible to produce components in terms of material, geometry, tolerance and strength etc. [2]. Additive manufacturing methods provide the capability to automatically produce components with various part designs including complex internal features. However, a number of limitations hinder its further development, such as limited materials available, long production times, diminished surface quality and reduced dimensional accuracy, compared to computer numerically controlled (CNC) machining. On the other hand, CNC machining technology, a subtractive process, is typically used for hard material machining, due to high accuracy and the relatively short production times achievable. Nevertheless, certain features like internal cavities are still difficult to produce due to limited tool accessibility. In recent years, the on-going industrial trend towards energy efficiency and material consumption requires new technology to be developed. As a result, the concept of hybrid manufacturing begins to emerge [1]. However, none of these hybrid processes addresses the material consumption issue. Products that are out of tolerance are abandoned resulting in considerable waste and in turn, increased overall production and part cost.

Process planning techniques have nowadays been widely used in various domains of production. Generally, process planning comprises of the selection and sequencing of processes and operations to transform a chosen raw material into a finished component [3]. Nonetheless, the majority of process planning research focuses on machining technology. Furthermore only limited process planning approaches have been developed for the hybrid processes.

In this paper, a hybrid process entitled iAtractive, combining additive (i.e. Fused Filament Fabrication, FFF [4]), subtractive (i.e. CNC machining) and inspection, along with a reactionary process planning algorithm is proposed. This will provide the designer with enhanced manufacturing capability and flexibility. The process planning algorithm enables a part to be manufactured either from zero or an existing part. The major elements for realising such an algorithm are described in detail in the proceeding sections. Finally, two case studies were conducted. In the first case study, the test part consists of internal features has been accurately manufactured as one complete unit. Three identical parts in the second case study were manufactured from three existing parts with different features. These case studies demonstrate the efficacy of the proposed hybrid process and the process planning algorithm.

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2. Review of the related work

2.1. Current research on hybrid manufacturing processes

Combining CNC machining processes with additive processes may provide new solutions to the limitations of additive processes [5] due to the high accuracy, improved quality and speed that machining processes offer. Jeng and Lin [6] used a laser to melt the mixed powders (Fe, Ni and Cr) and once one cladding operation was accomplished, the surface of the cladding was milled in order to achieve the desired accuracy and maintain a flat surface for the next cladding operation, until the entire mould was produced. Liou et al. [7] and Zhang and Liou [8] incorporated a laser cladding unit with a five-axis milling machine, where any deposition feature can be built in the horizontal direction by rotating the workstation. Thus, the need for supporting material during the deposition is eliminated, further reducing build times. Karunakaran et al. [9], and Suryakumar et al. [10] retrofitted a 3-axis milling, which was used to face mill each slice built by metal inert gas (MIG) and metal active gas (MAG) welding. However, there is no robust process planning approach developed. The hybrid process just deposits one layer followed by a face milling operation. Further layers are deposited and machined until the entire part is produced. Therefore, Karunakaran et al. [11] argued that the need to face mill each layer is the major barrier for reducing production time. Furthermore, Lanzetta and Cutkosky [12] utilised Shape Deposition Manufacturing process (SDM), which is the combination of material deposition and milling, to build smooth and sculpted 3D contours of dry adhesives which could be used to aid human and robotic climbing.

The integration of laser heating or ultrasonic vibration and traditional milling/turning/grinding processes has been identified as an effective method to improve surface quality and increase tool life [13]. In the laser assisted machining process, a focused laser beam is used as the heating source to irradiate the workpiece for improving the materials machinability. While the material is locally heated and softened, it is removed by a conventional cutting tool [14]. Dumitrescu et al. [15] attempted to use a high power diode laser, suggesting that higher machining efficiency and better metal absorption can be expected. Anderson and Shin [16] proposed a new configuration in which two laser beams simultaneously irradiate a machined chamfer and an unmachined surface adjacent to the chamfer, respectively. It is the simultaneous application of mechanical machining by spindle rotation, and ultrasonic vibration by a high frequency axial ultrasonic oscillation of the cutting tool or workpiece [17]. Uhlmann and Hübert [18] applied the superposition method to combine a grinding operation with a secondary oscillation, by which the oscillation of the grinding tool was excited by piezoelectric oscillators. The tool was vibrating in a vertical direction while it was cutting material horizontally. However, in the experiments by Yanyan et al. [19], the ultrasonic vibration actuator was adhered to the workpiece instead of the diamond grinding tool, which led to the oscillations of the workpiece. With vibration assistance, tool wear can be reduced and Lauwers et al. [20] further developed a tool path generation algorithm for machining of ceramic components, obtaining better surface quality.

Other combinations of manufacturing processes are also researched. Zhu et al. [21] investigated the mechanical-electrochemical machining of small holes by ECM and grinding, where a metal rod with abrasives was used as the cathode tool to mechanically and electrochemically machine the workpiece part. Dhokia et al. [22] developed a novel cryogenic CNC machining method, which sprays liquid nitrogen onto the workpiece (i.e. soft elastomer) to rapidly reduce the material to its glass transition temperature. This increases the stiffness of the low-density workpiece, allowing it to be machined by conventional CNC machining methods. In the paper by Araghi et al. [23], a stretch forming process was employed for pre-forming rough shapes. An asymmetric incremental sheet forming (AISF) process was subsequently carried out to produce the final parts.

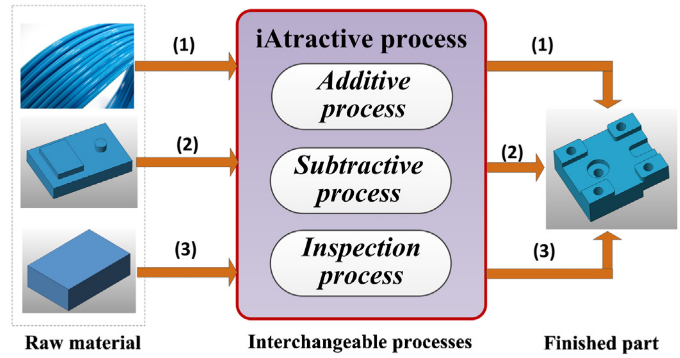

Fig. 1. Vision of the iAtractive process production.

2.2. Process planning for hybrid processes

Very limited research has been reported on process planning of hybrid manufacturing. This is because there has not been a need for it since manufacturing has been limited to singular independent processes. Kerbrat et al. [24] used a design for manufacturing (DFM) approach to analyse features in the design stage and subsequently identified which features would benefit from being made either by machining or additive process in terms of feature complexity. In the combination of additive and subtractive processes, a typical process planning approach is to face machine the top of each layer after it is deposited [6]. Hu and Lee [25] introduced a concave edge-based part decomposition method, which splits the part into a number of subparts to eliminate undercut edges during machining. Ruan et al. [26] developed a process planning approach that can generate non-uniform layer thickness and tool paths for laser cladding and CNC machining by taking into account tool collisions.

3. A novel concept of hybrid manufacturing process

The concept of hybrid manufacturing (iAtractive) currently being investigated at the University of Bath consists of combining additive, subtractive and inspection processes [27]. This is based on the need to reuse and remanufacture existing parts or even recycled and legacy parts; reduce the amount of material used; enhance the flexibility of CNC machining and improve the accuracy of FFF process. Incorporating an additive process releases design constraints often caused by tool accessibility issues in CNC machining. Using CNC machining capabilities the final part can be produced with a high degree of accuracy comparable to that of an entirely CNC machined part. Furthermore, dimensional information of the existing part can be obtained by using an inspection technique enabling the existing part to be further manufactured by an additive and/or subtractive process, providing new enhanced functionalities. This indicates that the iAtractive process is not constrained by raw material in terms of shape, geometry or features. The vision for the proposed hybrid process production is depicted in Fig. 1, where raw material can be (1) zero (filament for deposition from zero); or (2) an existing/legacy product; or (3) a billet. By using the additive, subtractive and inspection processes interchangeably, the given raw materials can be further produced to the finished part.

The iAtractive process is shown in Fig. 2 and is outlined as follows: (i) Raw material is first inspected by using a Coordinate

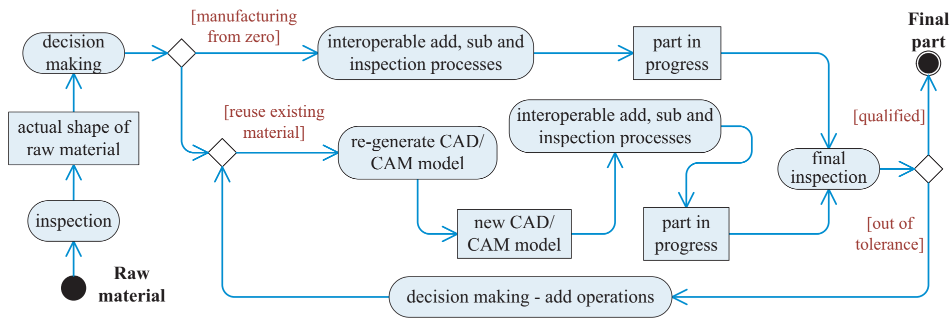

Fig. 2. The proposed iAtractive process.

Measuring Machine (CMM) [28]. The importance of this step is to obtain the actual geometrical attributes of the raw material, which becomes the basis of the process plan for determining subsequent operations. It is noted that the raw material is seen as zero if filament or other material that is specifically used in additive processes (e.g. powder and liquid) is given. (ii) The part design (CAD model) is input into the decision-making algorithm. Decisions are then made on whether to manufacture the product from zero or reuse the existing part geometry to further process it to the final shape. (iii) For the first scenario, additive, subtractive and inspection processes are utilised interchangeably in a serial manner, by which the final part will be produced. (iv) For the second scenario, a new CAD model is generated according to the dimensions of the existing part. The new model shows the shape of the rest of the material required to produce the designed part. The existing part is further manufactured to the final geometry and part tolerances by adding and/or removing material. (v) At the end of both scenarios, the part is further inspected identifying which dimension is out of tolerance. If this is the case then further decisions can be made on whether to add more manufacturing operations until the dimensions are in tolerance.

4. A reactionary process planning algorithm for iAtractive process

A logical reactionary process planning algorithm (RP^2A) is proposed and contains two major stages, namely generation of static and dynamic process plans. The overall goal of RP^2A for the iAtractive process is to generate the process plan from a given part design. The additive, subtractive and inspection processes are used interchangeably to produce the part in the shortest time possible and with reduced material consumption. This section presents the first part of the algorithm, which is used in the scenario where the part is produced from zero. The second part of the algorithm for material reuse will be described in the proceeding section.

4.1. Generation of static process plan

Generation of static process plan for RP^2A involves ten major steps as illustrated in Fig. 3.

Feature interpretation and manufacturability analysis: the first step is feature interpretation, which involves extracting and interpreting features from the defined CAD model. The identified

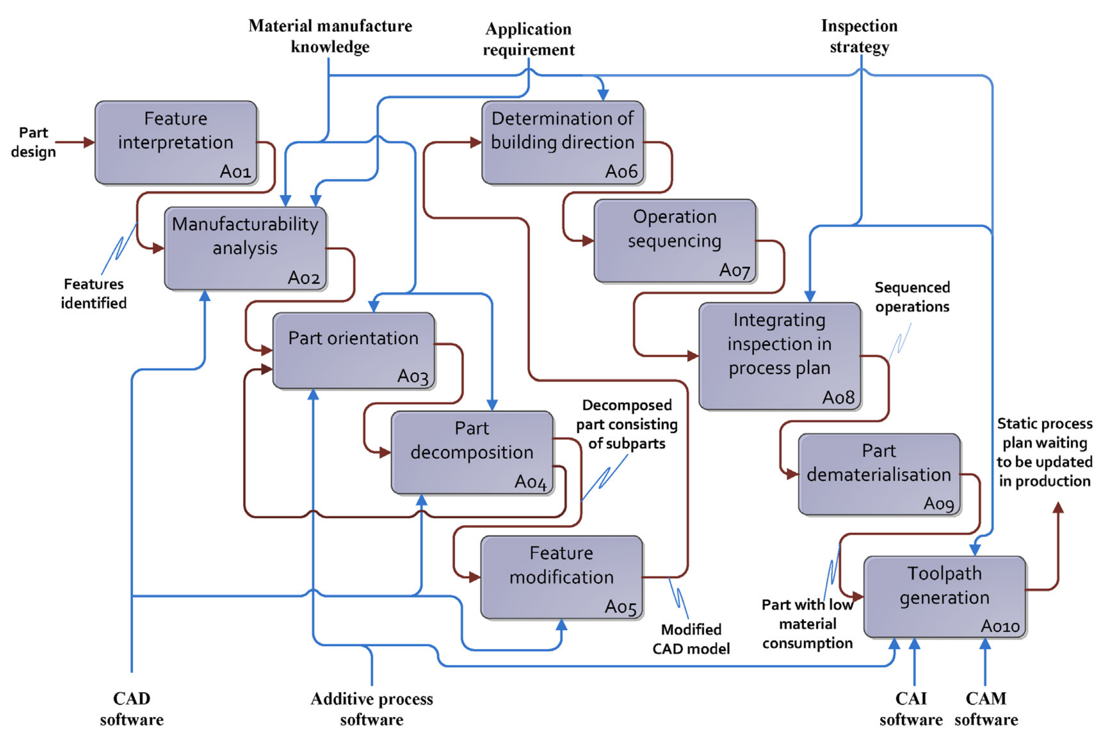

Fig. 3. IDEF0 view of the reactionary process planning algorithm for the generation of static process plans.

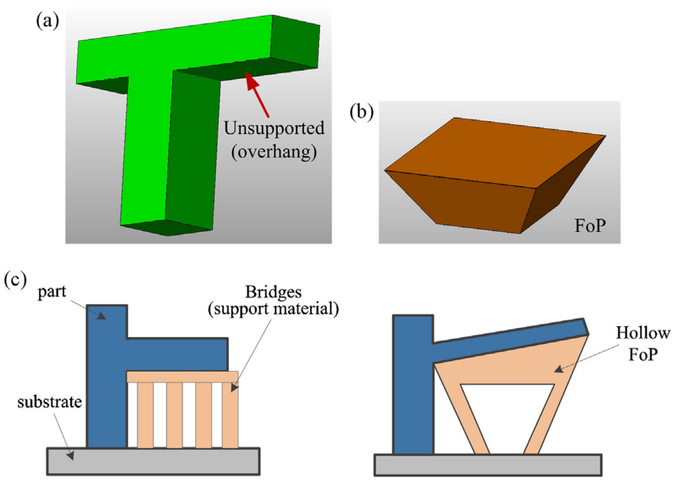

Fig. 4. Overhanging feature and the support material structures.

features are then analysed in the manufacturability analysis module. Manufacturability analysis falls into two activities, machinability and buildability analysis. Any features such as internal and concave features that would cause potential tool accessibility problem are detected as part of the machinability analysis. Features that can only be manufactured by an additive process (e.g. a pocket with sharp corners) or which require special tooling, implying additional tooling costs, will also be identified. Buildability analysis largely identifies overhanging (see Fig. 4a) and thin wall features. In addition, nozzle collision detection will also be carried out to indicate any possible collisions between the deposition nozzle and existing features in the case that the existing part is used.

Part orientation: orientation is an important process parameter that affects part strength, dimensional accuracy, surface finish, part build times and cost etc. However, only build times and material consumption is taken into account in this step as the part will be finish machined. Since less material requires shorter build times, the CAD model is orientated in a position, in which the part can be fabricated without or with less support material. By orientating the green part in Fig. 4a, the volumes of the support material required can be different. As a result, two support material structures are suggested, namely bridges and hollow frustum of a pyramid (FoP) (see Fig. 4b and c).

In total, there are 8 support structures and all of them are the variations of the above two structures depending on the geometrical attributes of the given overhanging features. Eq. (1) is used for calculating the volume of one variation of the FoP support. It is noted that no support structure is constructed at this stage. The equation as shown below is only used in RP^2A to identify the part orientation, where the lowest volume of support material is needed.

$$V = \frac{1}{2}b(L - \frac{\sqrt{3}}{3}h)(2H + h) - \frac{\sqrt{3}}{3}(L - \frac{\sqrt{3}}{3}h + b)H^2 - \frac{4}{9}H^3 \qquad (1)$$

where, V is the volume of support material; L is the length of the overhang; H is the absolute height of the overhang; h is the relative height of overhang if there is an inclination angle; b is the width of the overhang.

The most important criterion is build time. A multi-factor regression model has been developed, estimating the time used in the additive process for manufacturing the part from different directions. The model will be presented in the next subsection. By considering build times and material consumption, a decision can then be made, specifying appropriate orientation.

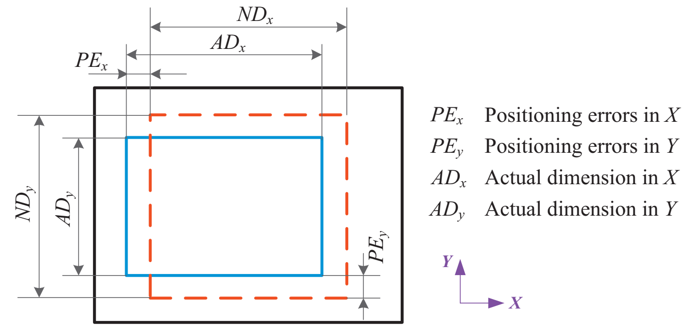

Fig. 5. Dimensional and positioning deviations.

Part decomposition for manufacturing: if the part has internal features that cannot be machined because of cutting tool inaccessibility, it will be decomposed into a set of subparts, which allows the internal features to be first produced to the required dimensions and tolerances. Subsequent features are then added. The relationship between two subparts is categorised as parent and child. A subpart that has to be deposited onto another subpart is considered to be a child part.

The aim of decomposition is to enable complex part to be manufactured as a whole rather than producing a number of pieces and assembling them together. The decomposition process has to satisfy the following requirements: (1) the features on the subparts should be exposed; (2) the subparts can be fixed on the fixtures of the machine tool because they will be finish machined; (3) no deposition nozzle collision while depositing a child part onto a parent part; (4) the surface of the parent part where the child part is built on has to be flat. The output of part decomposition is a set of subparts, which will be further optimised and merged in the following modules.

Feature modification for different processes: due to the various errors caused by FFF machine gearings, process parameters (e.g. layer thickness, diameter of deposition nozzle) and material shrinkage, the dimensional accuracy of fabricated plastic parts are normally not as high as that of CNC machined parts. Fig. 5 gives an example (top view) of an actual fabricated feature (blue) as compared to the nominal feature (red dashed line), when a boss is added onto a block. In addition, part distortions occur when a child part is built onto a parent part or material is added onto an existing part. This essentially indicates more material (i.e. warped part) has to be removed. Hence, the related features have to be modified accordingly for compensating dimensional, positioning errors and distortion errors, ensuring the real part fabricated is slightly bigger than its nominal dimensions. This allows the machining process to finish machine the part, achieving the required surface quality and accuracy. Furthermore, support structures will be added to the CAD model if overhangs have been identified in the previous stage.

Determination of build direction and sequencing of additive and subtractive operations: if the part has been decomposed into a number of subparts, the build directions of these subparts have to be determined. This is due to deposition tool collisions that may happen while depositing material on one certain direction or the specific operation sequence that is restricted by the limitation of the FFF process i.e. material cannot be built without support. The major concern for determining the correct build direction is build time and deposition tool collisions. Moreover, when multiple build directions are available, the production time estimation model will be used to determine the best direction in terms of production times.

For operation sequencing this algorithm first identifies feasible sequences followed by the determination of the most appropriate sequence where the lowest production time is achievable.

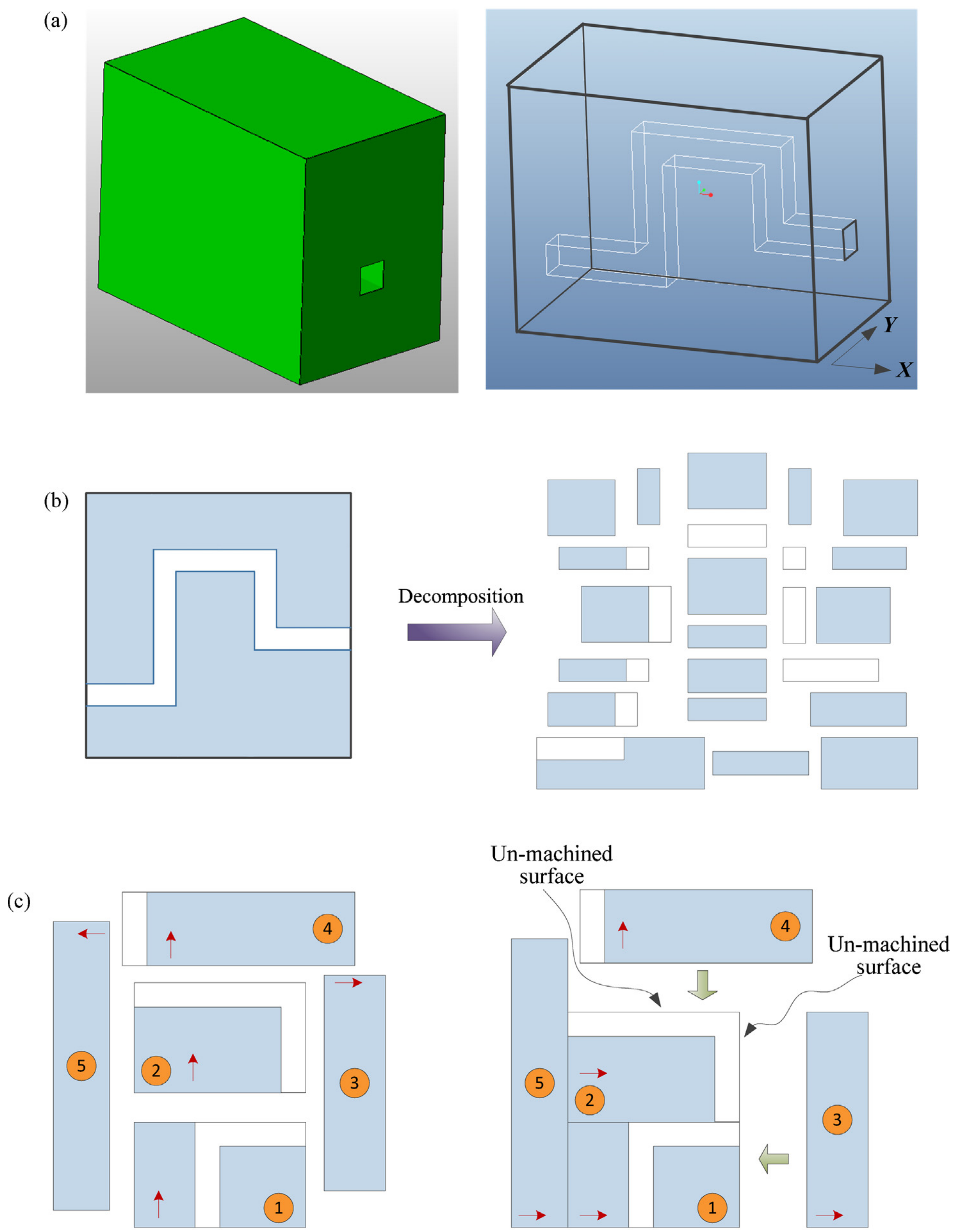

Fig. 6. Operation sequencing and merging of subparts.

Three types of precedence constraints are considered, which are dimensional accuracy constraints, parent and child constraints, and machining constraints. For the features where low surface roughness and high accuracy are specified, a machining operation must come after the additive operation. Parent and child constraints mean the operations for making the child feature have to be scheduled after the operations that are used to produce the parent part. The machining constraints largely include fixture interaction, tool interaction, datum interaction, feature priorities, fixed order of machining operations, thin wall interactions and material removal interactions. Furthermore, operation changeover times are also considered since switching between additive and subtractive operations requires extra time such as datum set-up. Finally, cutting tool accessibility is also taken into consideration if each internal feature is required to be finish machined. An example can be found in Fig. 6, where each surface of the part is required to be machined to achieve the correct surface quality and tolerances. Fig. 6a is the internal view of the part, which has five connected pockets. For better representation, round corners are intentionally ignored in Fig. 6b. The decomposed result is also shown in Fig. 6b. Twenty three subparts are merged into 5 as some of them have the same build directions whilst satisfying the criteria described above (see Fig. 6c). The overall sequence is to manufacture subparts from 1 to 5 by interchangeable FFF and CNC machining operations (red arrows denote the build directions). Fig. 6d demonstrates the consideration of tool accessibility where the order sequence is to manufacture subpart 5, 1, 2, 3 and 4. Even though subpart 2 has been finish machined, the two surfaces highlighted by the arrows become rough (un-machined) again once subpart 3 and 4 are added. In this case, these two surfaces cannot be machined anymore as the tool can no longer access the pocket on subpart 2.

Integrating inspection process and generating process plan: integrating inspection in the iAtractive process means that inspection becomes a value adding process. Inspection is also the enabler for transforming a static process plan into a dynamic process plan,

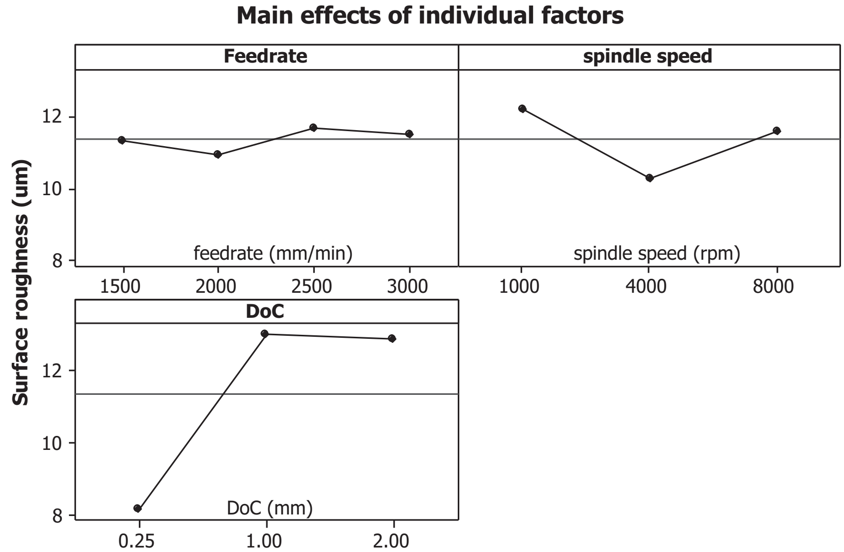

Fig. 7. The main effects plots for surface roughness.

which will be presented in the next subsection. Having added the inspection operations to the previous process plan, the operation sequence is now completely organised.

Part dematerialisation: part dematerialisation can be defined as manufacturing a product with the minimum amount of material possible, without compromising on part integrity or overall functionality. CNC machining is not capable of producing such parts. However, the iAtractive process enables new opportunities to dematerialise parts by using less material through material re-distribution and re-densification. Evolutionary Structural Optimisation (ESO) technique can be used to analyse the part structure, identifying structurally efficient designs [29]. ESO is based on the concept of gradually removing inefficient material from a structure so that the residual shape evolves towards the optimum. By applying the ESO technique, the interior porous structure of the part is obtained, consisting of different areas of material densification. This provides enhanced structural functionality and integrity only where it is actually required in the part. Even though this has been recognised as an important element in RP^2A, it will be developed as part of future work.

Generation of deposition path, machining tool path and measurement programme: deposition paths based on the dematerialization results (if ESO is applied), machining tool paths and inspection programme are generated by the use of open source and commercial software, such as RepRap host [4] and Delcam Powermill [30]. The most significant function in this step is to apply appropriate machining process parameters for layered parts [31].

The three machining parameters selected were, feedrate, spindle speed and depth of cut (DoC). A series of slot milling experiments were carried out [31]. The surface roughness was measured and the results were statistically analysed, suggesting that DoC is the most significant factor that determines surface roughness. The main effects of each individual factor are plotted in Fig. 7 below. It was found that the change of feedrate has the smallest effect on the surface quality, implying that increasing feedrate is a feasible way of significantly reducing machining time for machining subparts. Finally, it was concluded that selecting lower DoC (e.g. 0.25 mm) is more likely to obtain less surface roughness. A cutting speed of 4000–5000 rpm together with a high feedrate is recommended.

To this end, a static process plan has been fully developed and it will be updated during the production phase by adding new operations to the plan.

4.2. *Generation of dynamic process plan*

Due to the integration of inspection, the iAtractive process is able to react promptly to quality changes. Dynamic process plans are generated during the production of the part based on the knowledge of the static plan generation, according to the feedback of inspection information. Operations are adjusted and added into the static process plan if necessary. As introduced in the last section, inspection operations are used at the beginning of the iAtractive process to identify the shape of the existing part and are also used at the end of the iAtractive process to measure the dimensions of the finished part. Moreover, inspection operations are added before a machining operation starts, identifying how much material should be removed from the deposited feature. If the deposited feature is smaller than its nominal size, as identified in the inspection operation, further deposition operations will be added before the machining operation is executed (an example is given in the case study section). Furthermore, inspection operations are conducted before depositing a child part onto an un-machined parent part due to the differing heights of the parent part that could result in the change of depositing parameters.

4.3. *A model for production time estimation*

In addition to material consumption, the iAtractive process also aims to manufacture products in the least amount of time possible. The total production time for manufacturing a part is defined as:

$$T = T_a + T_s + T_c + T_m \quad (2)$$

where T is the overall production time, T_a is the time for additive process, namely build time, T_s is the time used in subtractive process, T_c is the switching time between additive and subtractive operations, which includes machine set-up time, T_m is the inspection time. Machining time estimation has been well researched. A method proposed by Heo et al. [32] is adopted in RP^2A. Since the part is decomposed into a number of small subparts with fewer features, the inspection time can be simply considered as constant at this stage. By contrast, the building process consumes considerably longer time than that of other processes utilised. For example, the build time for producing a feature with volume of 50 cm^3 could be up to 20 times than the machining time for machining such a feature. Differing build direction leads to variations in the build time.

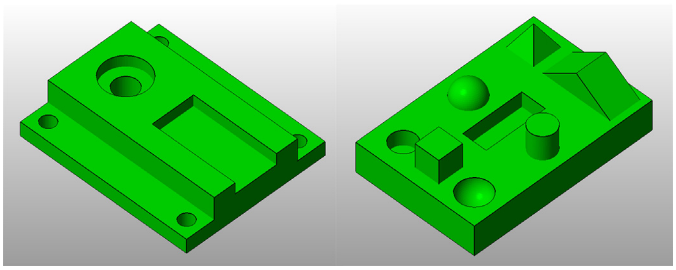

Fig. 8. Two test part examples for build time estimation.

Therefore, a build time estimation model is needed, which is able to determine part orientation.

A full representation of the build time for fabricating a single part has been developed and is depicted in Eq. (3).

$$T_a = \sum_{i=1}^{I} T_i + T_{bed} + T_{heater} = \sum_{i=1}^{I} \left[\sum_{j=1}^{J} \left(\frac{S_{re\_j\_xy}}{V_{xy}} - \frac{V_{xy}}{A_{xy}} \right) + \sum_{k=1}^{K} \left(\frac{2L_{ret\_k}}{V_{ret}} + \frac{S_{pr\_k}}{V_{pr}} - \frac{V_{pr}}{A_{xy}} + T_{delay} \right) + \frac{\theta}{V_z} \right] + T_{bed} + T_{heater} \quad (3)$$

where the part is sliced into I layers, T_{bed} and Theater are the time for preparing heated bed and heater, respectively, $S_{re\_i\_xy}$ is the jth ($j \in [1,J]$) nozzle repositioning distance before depositing the jth continuous deposition path in XY plane, V_{xy}, V_z V_{pr} and V_{ret} are the nozzle repositioning speed (in XY plane and Z axis), moving speed during deposition and the filament retraction speed, respectively, A_{xy} is the acceleration, S_{pr_k} is the distance of the kth ($k \in [1,K]$) continuous deposition path; L_{ret_k} is the length of the filament retracted before depositing kth deposition path, θ is the layer thickness in $(i+1)$th layer. θ is the layer thickness (unit:mm).

According to Eq. (3), it can be identified that increasing nozzle speed and layer thickness and reducing nozzle repositioning distance can reduce build time. A factor named intermittent factor (η) is defined for representing the ratio of nozzle deposition distance and repositioning distance. It is also noted that Eq. (3) itself does not directly reflect the relationship between part dimensions and build times, which are the most accessible geometrical information for RP^2A. Thus, a number of test parts have been designed with different part volumes, heights, porosity and intermittent factor (two example test parts are shown in Fig. 8).

These test parts were then further modified with varying levels of volume, height, density and intermittent factor. The build times were precisely calculated by applying Eq. (3). The results were analysed using analysis of variance (ANOVA) and regression techniques, iteratively. Selected results are listed in Table 1, indicating that the interaction between volume and porosity is the most significant factor followed by the part volume. The interaction between the height of the part and intermittent factor is of secondary significance. In addition, the adjusted R square represents the regression confidence, which is highly satisfactory while comparing the actual and predicted results.

Table 1
Selected ANOVA results of build time estimation.

Factors	Adjusted R square	P-value
Intercept		0.546605
Part volume (V)		<0.0001
Part height (H)		0.262786
Volume × porisity ($V \times \rho$)		<0.0001
$H \times \eta$		<0.0001
Regression mode	99.980%	

A multi-factor regression model has been developed in Eq. (4), where ε is uncertainty in the actual experiments. It is noted that differing part heights resulting from part orientations do not significantly affect build time in creating identical parts, but it is still included in the equation as the combination of part height and intermittent factor is of significance.

$$T_a = 168.33 + 23.56V + 9.44H + 160.19V\rho + 78.17H\eta + \varepsilon \quad (4)$$

To validate the regression model, 48 additional cases of different combinations of V, H, ρ and η were used. The actual and predicted build times have been compared by using t-test technique and indicate that no significant difference was observed. The model is therefore considered to be capable of dealing with determination of part orientation, build direction and operation sequencing with <12% deviation.

5. Decision-making for manufacturing from existing parts

The second part of RP^2A is the decision-making engine for manufacturing components from existing parts, which also includes legacy products.

Two types of constraints that affect the selection of manufacturing strategies has been defined, namely, global constraints and local constraints. Local constraints are referred to geometrical and positioning dimensions. Local constraints only deal with the selection of manufacturing strategies based on the dimensions of the existing part features identified in the inspection process. Global constraints focus on application requirements (in terms of tolerances and surface quality), material consumption and positions of holes in part design. Global constraints significantly restrict the number of manufacturing strategies that can be used. For instance, for a component–which can be both manufactured by FFF process only and by FFF followed by a finish machining operation–cannot be solely fabricated by FFF in certain application areas where high dimensional accuracy is required. Global constraints are applied at the end of the decision-making process to finally determine the manufacturing strategies.

Existing parts are classified based on features, which are existing part with a boss, pocket, step, slot, hole, planar surface and combinations of any of these features. Individual features are categorised into non-final and final features. Obviously, final features are the features required on the final part. Non-final features are the features on the existing part but are not the desired features on the final part.

The iAtractive process first measures the given existing part for obtaining its dimensions which are the input for the decision-making engine. The existing part is then classified as containing non-final features or final features. Feasible manufacturing strategies are proposed according to the dimensions of the features on the existing part by taking FFF process capabilities into account, such as producing overhangs and deposition head collisions. Some of the typical strategies are outlined as follows: (1) directly add material onto the existing part, then interchangeably add and subtract and inspect (iASI) until the part is finished; (2) remove the existing feature to get a planar surface, then iASI; (3) for an existing feature that is included in another feature, remove the outer feature, then iASI; (4) machine the existing features to the final dimensions directly; (5) and (6) add material inside or outside the existing feature until the height of the newly deposited material reaches the same height as the existing feature, respectively, then iASI. Fig. 9 is a partial representation of the complete decision tree, which shows the available manufacturing strategies by applying local constraints. L, W, D, H, Dia denote length, width, height, depth and diameter, respectively; p and b denote pocket and boss, respectively; D_f is the vertical distance from the existing feature to its

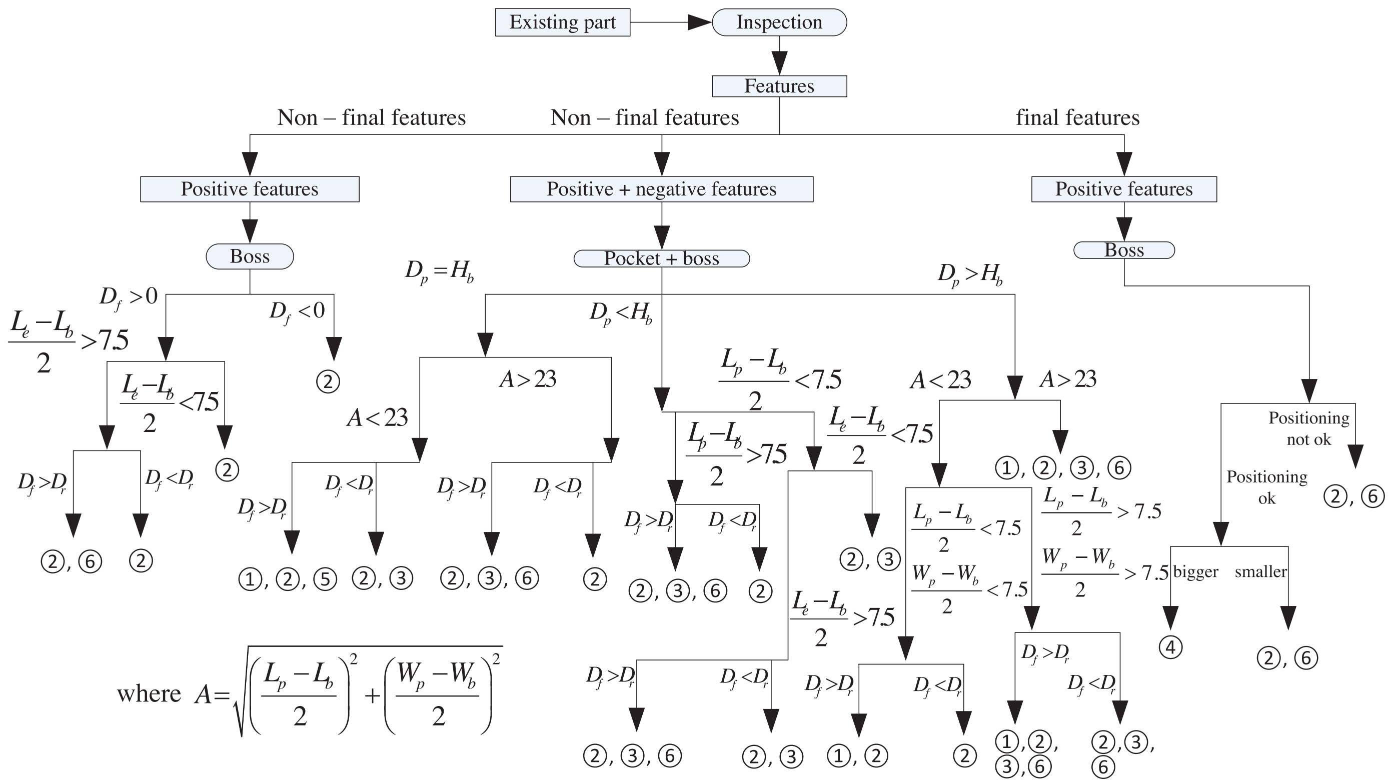

Fig. 9. A partial representation of the complete decision tree.

adjacent final feature; FFF is able to make bridges without support but the printed surface is not flat until a certain number of layers have been deposited after producing the bridges, which is denoted by D_r. The value of D_r depends on the bridge length the FFF process produces; 23 mm is the longest bridge length that can be produced. On the other hand, the length of the bridge to be manufactured is dependent on the dimensions of the existing features; the deposition head is $15 \times 10\,mm^2$ on the XY plane; all the units are mm in Fig. 9. A typical example is: if an existing part has a pocket (non-final) and the length or the width of the pocket is smaller than 23 mm, a feasible strategy would be to directly deposit material until the near-net shape of the part is built. If the length and width are both larger than 23 mm, the pocket can be filled and the deposition process continues until the near-net shape is obtained.

6. Case study

Two case studies were conducted to demonstrate the feasibility of the iAtractive process together with the proposed process planning algorithm. The FFF process is now able to produce a low melting point alloy (tin, bismuth and indium). At the time of the development of RP^2A, a thermoplastic called Polylactic acid (PLA) was used to demonstrate the iAtractive process.

A block with four connected pockets and a hole is shown in Fig. 10a. All the corners (except the corner where the hole is located) are round corners with 3 mm radii, but for better representation they are ignored in Fig. 10b. All the surfaces require finish machining. As a result, the part was decomposed into a number of subparts, which were then further merged into 5 subparts as shown in Fig. 10c. However, it was found that subpart 5 (red) was out of tolerance during production (see Fig. 10d). RP^2A subsequently added three more operations to the process plan, namely, re-machine the side surface of subpart 5, then add material onto it and finally finish machine it to the correct tolerance values. The finished part is shown in Fig. 10e. For showing the internal features, the part has been sectioned (see Fig. 10f).

In Fig. 11, three existing parts were provided, which were a part with a boss and a pocket, respectively, and a finished part. The

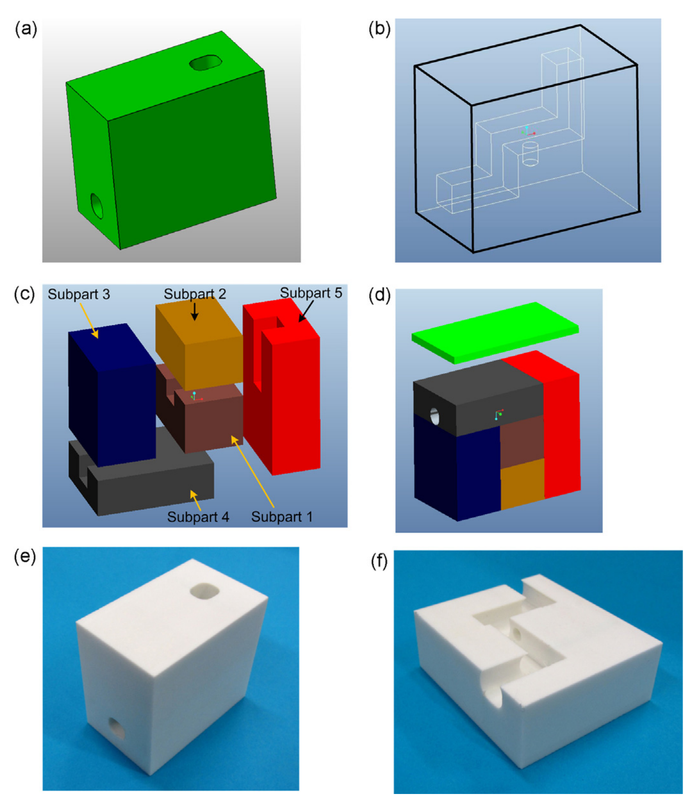

Fig. 10. Test part 1.

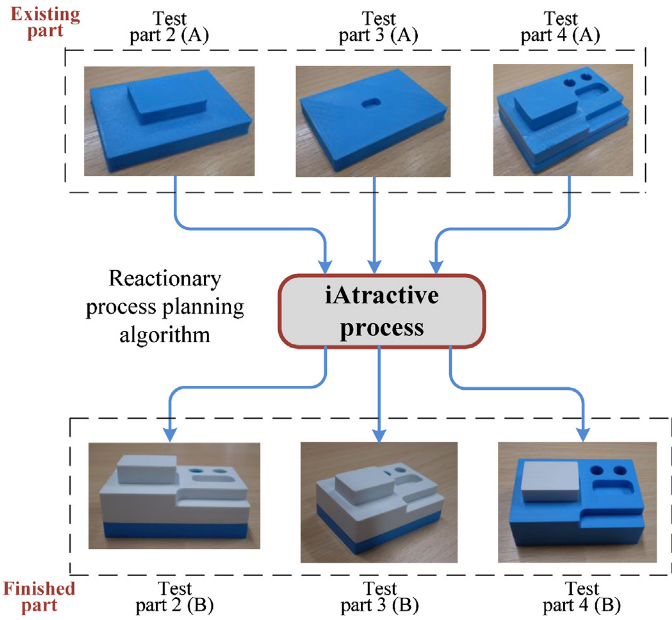

Fig. 11. Test part 2, 3 and 4 (existing parts).

finished part has been identified in the final inspection process as being out of tolerance since the actual dimensions of the boss feature was $19.5 \times 17.8 \times 8.3\,\text{mm}^3$, whereas the nominal values are $20 \times 18 \times 8\,\text{mm}^3$. Therefore, the decision-making engine suggested appropriate manufacturing strategies, by which the existing parts were remanufactured into the final products as illustrated in Fig. 11. These manufacturing strategies are as follows:

- *Part 2 (B)* was produced from an existing part (part 2 (A)) with a boss. Based on the measurement results, the decision-making process provided two options to reuse this existing part. One of the options was to remove the boss and subsequently add new material on to the machined surface. The part was finish machined and finally inspected to make sure the dimensions were in tolerance.
- *Part 3 (B)* was also manufactured from an existing part (part 3 (A)) with a pocket. The additive process was used to directly deposit layers on top of the existing part.
- *Part 4 (A)* was identified as an unqualified product in the final inspection process (see Fig. 2) as the dimensions of the boss were out of tolerance. Therefore, three independent operations were added in the process plan, where the original boss was removed and a new boss was added/deposited and subtracted/finish machined.

The blue material represents the existing parts and the white material represents the new material that was added and finish machined.

7. Discussion

After applying the RP^2A generated process plan for the manufacture of the test parts, the feasibility of the iAtractive process and RP^2A has been demonstrated. This process planning approach acts as an enabler for flexibly and accurately manufacturing complex parts that are traditionally impossible to produce by either individual CNC machining or additive processes. The production time can be significantly reduced compared to the state of the art methods presented by Jeng and Lin [6] and Karunakaran et al. [9], since the redundant face milling operations for each layer have been removed. The total material consumption can also be reduced as a result of being able to generate optimised support structures. The manufactured products can be achieved with a high level of accuracy and surface quality comparable to that of an entirely CNC machined part, whereas some of the features manufactured by adopting the Kerbrat et al. [24] approach could still remain inaccurate. The integration of inspection enables the iAtractive process to promptly respond to quality changes during production. Implementing the dynamic process plan, which is generated during production, enables the part to be manufactured appropriately, allowing the final product to be achieved with the correct tolerances. Existing parts can also be reused and reincarnated into other products by taking the dimensions of these existing parts into account and generating corresponding process plans.

However, as this approach has been developed based on prismatic part manufacture, it is not currently applicable to manufacturing free form sculptured surfaces. The current RP^2A still requires human intervention and thus a fully automatic RP^2A system needs to be developed, realising automatic part production. RP^2A also has the potential to manufacture functional parts with dematerialised structures by integrating ESO methods directly into RP^2A, by which material consumption can potentially be reduced by up to 75% [29]. In addition, RP^2A can be modified to fit other hybrid processes which combine laser cladding and CNC machining for metal part production.

8. Conclusions

A number of inherent technical limitations of individual manufacturing processes stimulate this research on hybrid manufacturing. This paper introduced a novel hybrid process combining additive, subtractive and inspection processes in a serial manner. A reactionary process planning algorithm is proposed, organising manufacturing operations and sequences, and determining appropriate parameters during production. It provides an intelligent solution to accurately manufacture complex products (i.e. internal features) in terms of production time, material consumption and reuse. Based on the given part design and available manufacturing resources, a static plan is first generated, which is ready for use but will be further updated according to the feedback of inspection operations during production. 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. Future work will focus on developing and extending RP^2A for accurately manufacturing parts with sculptured and internal features. A modified ESO method will also be developed, further reducing material consumption and introducing the concept of dematerialisation and re-densification.

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