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A Framework for Manufacturability Assessment and Minimum-Order-Machine Classification of Parts Fabricated by Additive-Subtractive Processes

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Abstract

Additive and subtractive manufacturing equipment used in SFF, require relative motion of additive and/or subtractive end effector tool with respect to the substrate. The relative motion is implemented with the help of mechanical drives. At the core of each mechanical drive is a rotary motor. Motivated by the classification and characterization of computer algorithms in the context of the amount of resources (such as time and storage) necessary to execute; this paper proposes classification of the design and corresponding manufacturing processes in context of the basic rotary motion. This paper proposes a novel method to classify different types of parts based on geometrical features, location of the geometrical features and relative location of the features. The manufacturability of any part, therefore, can be expressed in the context of a basic rotary machine. By expressing the geometry of a part in context of rotary machines, the manufacturing can be classified to follow a sequential Topology or parallel topology. This approach leads to the classification of manufacturing implements and the minimum-order-machine needed for fabricating a part.

Introduction

Manufacturing is defined as the transformation of raw materials into finished goods by means of tools and a processing medium. Manufacturing transforms the featureless substrate to a part with range of features. The primary intent of feature lies in offering functional intent as envisaged by the designer. The features of a part include-the geometrical features, the material features, optical features, the energy modified microstructural features and the intrinsic features such as weight, volume, etc. Features may be classified into intrinsic and extrinsic features. The intrinsic features refer to material composition or microstructure. Extrinsic features refer to the geometrical features.

Within the group of extrinsic features; however, certain features may be attributed to the manufacturing requirements and handling of the product. For the subject being addressed in this paper, a part is referred to as a finished homogeneous monolithic object. This paper is confined to the additive and subtractive manufacturing processes that transform rather featureless raw material into a product.

The geometrical features are added by additive (welding, cladding etc.), subtractive (milling, planning, shaping drilling etc.) or transformative processes (forging, molding.). This paper; however, focuses on the manufacturing processes pertaining to SFF processes and equipment. The SFF processes broadly include additive and subtractive processes.

While, most of the SFF processes are confined to the 2-1/2 axis platform [1], many novel platforms such as Multifab [2] use 6-axis manipulators.

Process specific commercial tools use production rules and constraint-based machinability evaluation techniques has been described, by Liu HongJun et al [3]. Another production-rule based approach was developed as an expert system for doing manufacturability assessment of sheet metal parts by Kashid sachin et al [4]. Within the welding based additive process the weldability index, has proposed by Pabolu, V K. et al[5]. Manufacturability Analysis Systems (MAS) , has been introduced by [6] to allow the evaluation of various manufacturability aspects during the design stage and consequently to reduce the costs and time to market of the designed products.

The following section describe analogy between algorithm and machine drive to establish a way to describe minimum order machine. Paper concludes with specific examples and a case study.

A brief discussion of algorithm complexity analysis

In the field of Computer Science, step by step approach to solve a problem, also referred to as algorithm, is quantified by defining its relationship between input size and computational resources. The computation resources are time (Computer clock) and space (hardware). Analysis of algorithm also provides an insight into methods that can be employed to optimize the resource requirement.

One of the popular methods used to classify the effectiveness of algorithm is known as Big "Oh" Representation. Big "Oh" Representation is used to evaluate the effectiveness of an algorithm by defining its relationship between input size and time and space used in the execution of the algorithm. This can not only aide in comparing two algorithms but also quantifying the efficiency of a process. Figure 1 depicts how the number of operations performed scales with input size for multiple different algorithms with different Big "Oh" Representations.

For example, an algorithm that would engage computer resources in linear proportion to input items, say size n; is classified as $O(n)$ or order of n. Similarly, another algorithm that would iterate through the list of items for each item in the list; e. g. sorting operations, may be classified as $O(n^2)$.

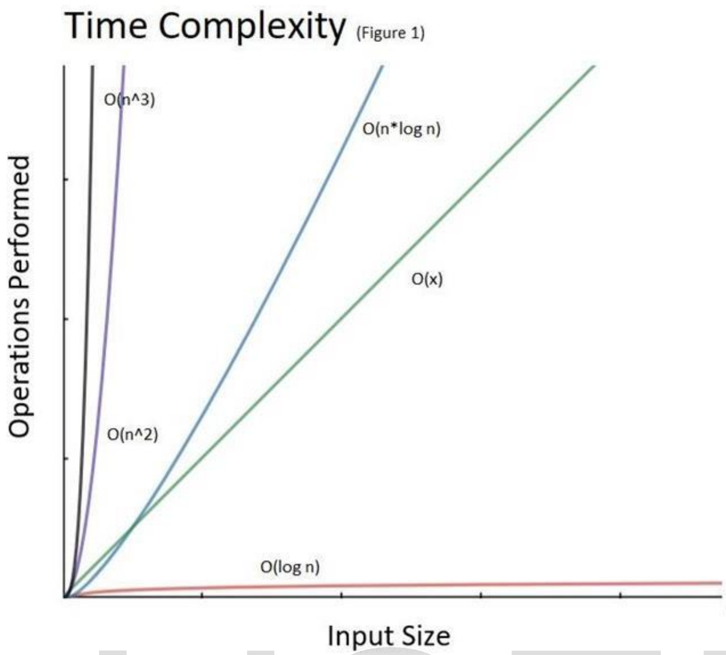

Figure 1 : Complexity order of different algorithms

Big Oh equivalence for manufacturing equipment

Inherent to the addition of geometric features by additive and subtractive manufacturing processes lies relative motion of an end effector and the substrate. Typically, the basis of each motion is a motor. Using various drives, the rotary motion is converted into linear, planar or 3D motion. The complexity and distribution of the geometrical features determine the total number of drives required for fabricating a part; therefore, the total number of motors needed to manufacture a part.

Motivated by the similarity of resource usage, we are proposing the minimum number of motors as the basis to classify the manufacturability of a part. Such a parameter would indicate the minimum degree of freedom of a machine required to build part in automated fashion; or equivalent number of human interventions needed to fabricate the part. This approach may indicate process redundancies and therefore has potential to improve the resource utilization. Alternatively, for a new process being developed such an indicator would suggest the required minimum degree of freedom for manufacturing automation. This leads us to another very important idea “minimum order machine”. A “minimum order machine” refers to a system with minimum numbers of motors required to build a system, that would allow a part to be fabricated in fully automated manner.

As described earlier, many SFF systems are integrating the additive and subtractive onto a common platform. Many of such systems are also optimizing the inherent degrees of the freedom of the system to conform with the geometrical features rather than, using zigzag and 2-1/2 axis-based approach. A pre-manufacturing analysis and minimum order machine classification can be used for process planning. Later sections describe a comparative study for the same.

Motors as the basis of spatial motion in manufacturing system

In a typical manufacturing implement geometric features are added by relative motion of an additive or subtractive end effector with resect to the substrate. The axisymmetric features are obtained by rotating substrate with respect to the tool (Figure 2).

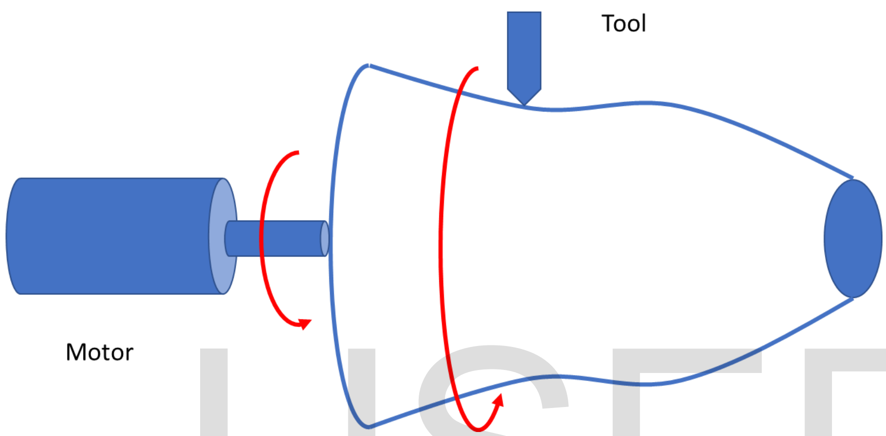

Figure 2 : Axisymmetric part fabricated by rotating a substrate and engagement of tool

Linear, planar and three-dimensional (Figure 3, Figure 4)features are obtained by using combination of one or more linear drives.

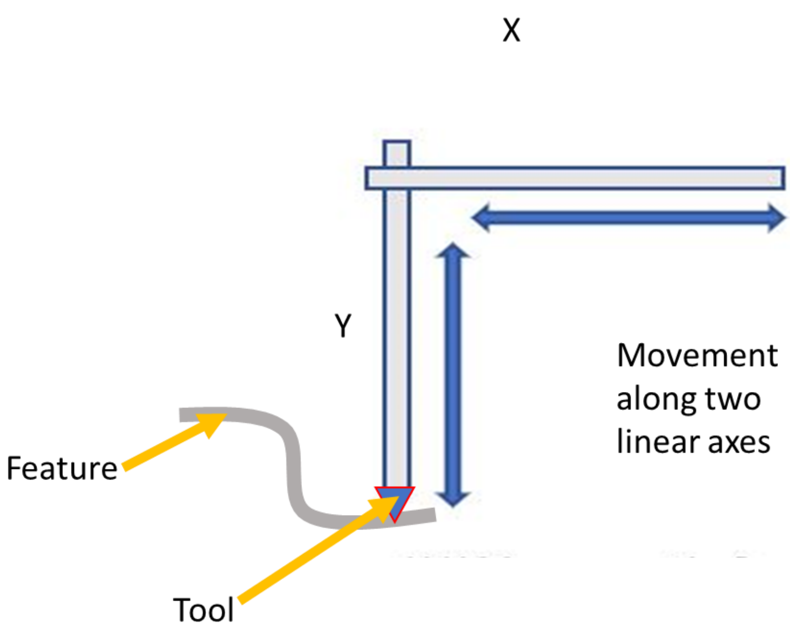

Figure 3 : 2D feature obtained by engagement of one motor along axes in X and Y direction

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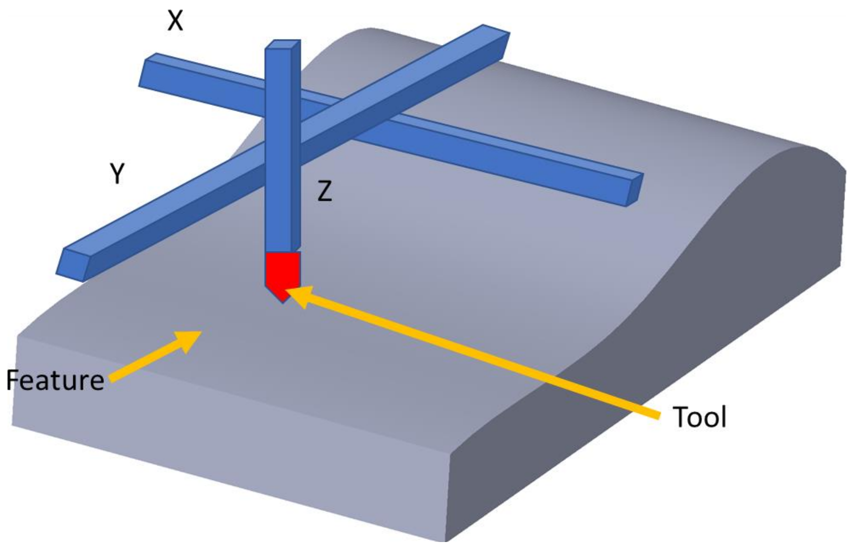

Figure 4 : 3D feature obtained by engagement of one motor along axes in X, Y and Z direction.

As described in Figure 5, Specialized drives are used to convert the linear rotary motion into linear motion.

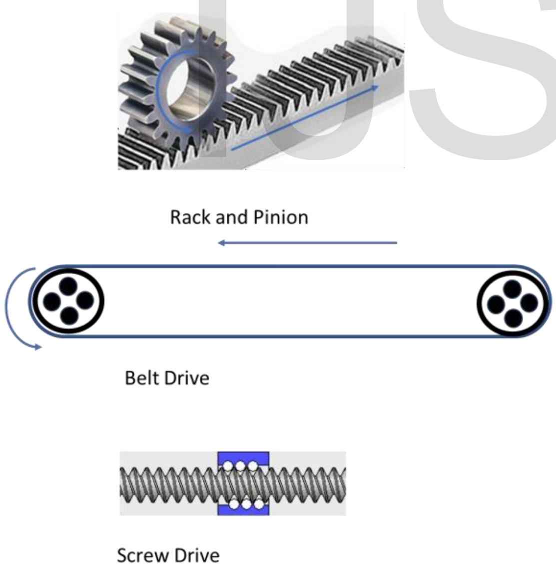

Figure 5 : Drives to convert rotary motion into linear motion

Order of manufacturing processes and minimum order machines for subtractive features

This section investigates and classifies geometric features in context of the minimum order machine.

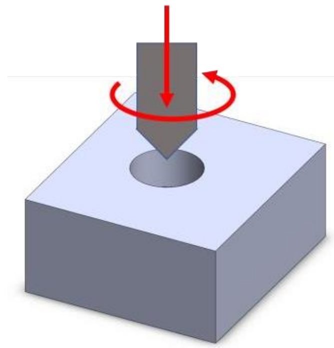

Figure 6 : Hole geometry created by a 2 order machine

A simple hole with the size same as the order of the drill tool geometry, can be machined by engaging two motors. The first motor spins the drill tool, and the second motor actuates the vertical motion. The minimum order machine for this process therefore is 2.

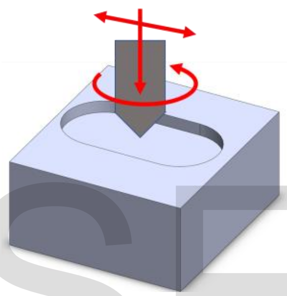

Figure 7 : Pocket geometry created by a 3rd order machine

However, if the tool geometry is significantly small order and is utilized to create a pocket like feature, the total order of the machine is 4. Similarly, a linear pocket depending upon the comparative size of the tool and the pocket would require a minimum 3 order machine.

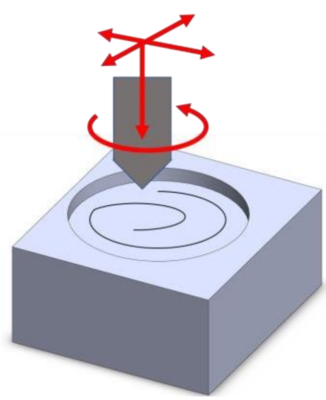

Figure 8 : Circular pocket geometry created by a 4 order machine

Additional degrees of freedom and therefore order of machine increase with the inclusion of median axis along different axis. As described in the figure, the part may be reoriented to utilize the existing same drilling and reciprocating tools, hence only additional degree of freedom need is that of the turning the part along its medial axis hence minimum order machine required to fabricate such a part is three.

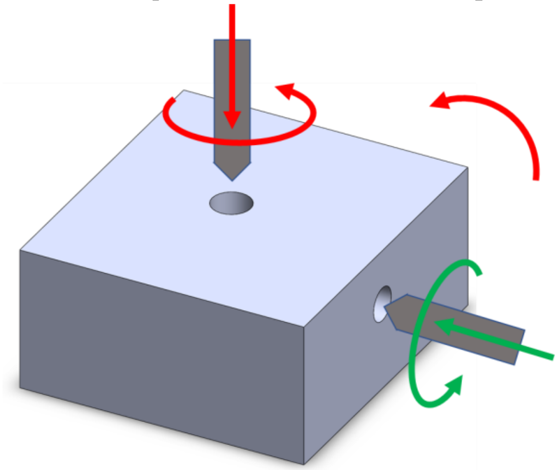

Figure 9 : Two features along different medial axes

Similar to the subtractive manufacturing processes in SFF, the features added by manufacturing processes may be classified per minimum order machine required.

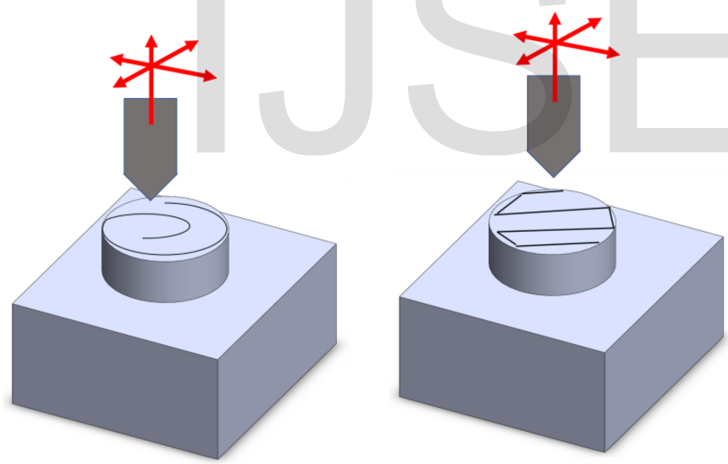

Figure 10 : Minimum 3 order machine to add feature by additive process

An SFF case study for minimum order machine

Figure 11 and Figure 12 describe two approaches for manufacturing a complex part. The subtractive process starts with a cylindrical block and material is removed by accessing along X, Y and Z direction. Additionally the turbine blades have continuously varying surface that requires the tool to be oriented normal to the turbine blade surface. Total minimum order machine; therefore, for this process is 6.

Manufacturing of additive process as displayed by , , has shown that the part can be built by combining on a rotary platform to a 3-axis material deposition probe. By coordinating the motion of the rotary axis along with the 3-axis material deposition probe the total minimum order machine is 4.

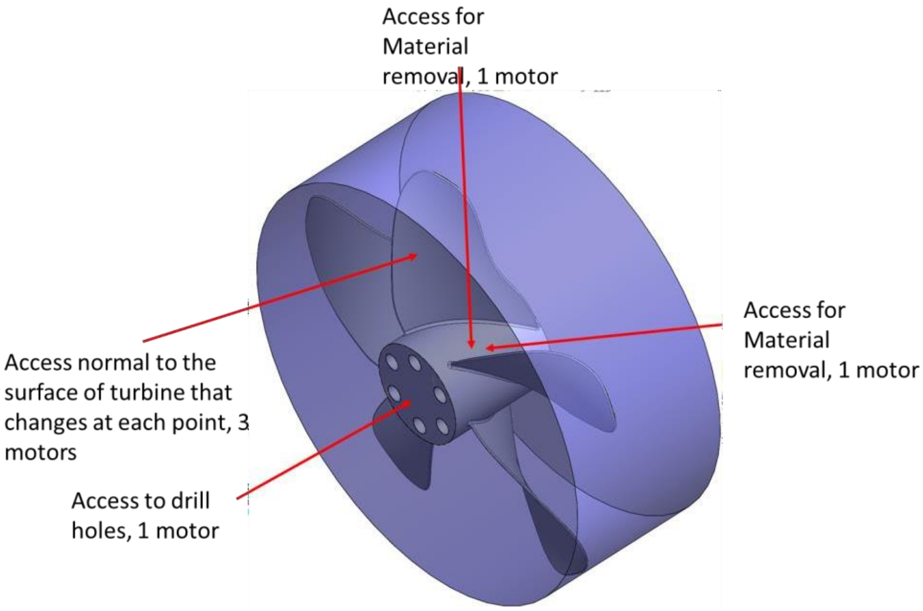

Figure 11 : A turbine manufactured by subtractive process requires access as well as orientation with the complex surface profile of the turbine therefore 6 minimum order machine

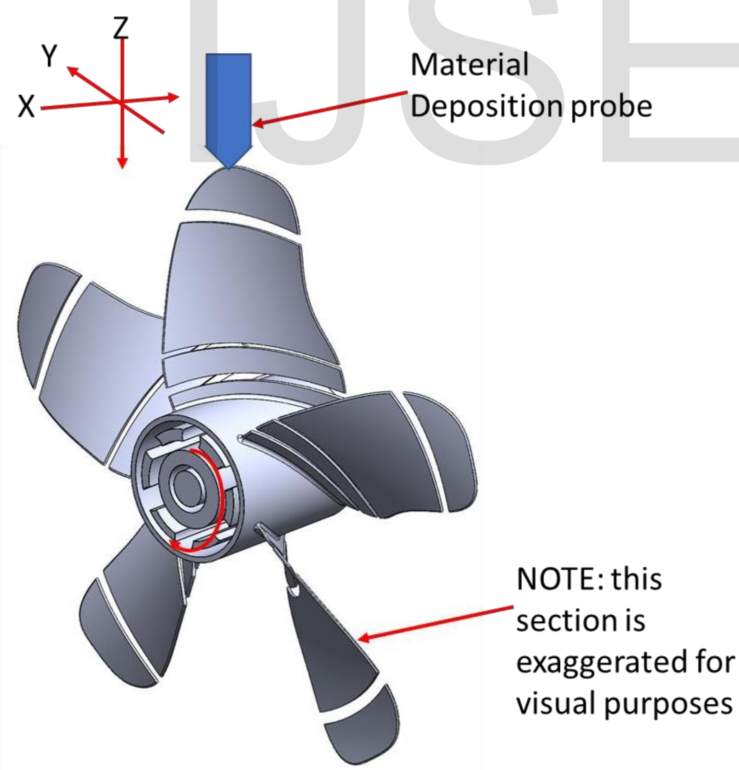

Figure 12 : Turbine manufactured by additive process uses a deposition probe that can move in x, y and z direction along with rotational axis hence minimum 4 order.

A detailed investigation into the minimum order machine suggests that we can remove two motors.

Summary and Conclusion

This paper describes a novel approach to look at spatial manipulators within the SFF-based manufacturing platforms. Examples to describe the minimum order machine with the motor as basis for spatial manipulation are provided. The paper concludes with and example where investigation into minimum order machine requirements suggest possible saving of two motors. A more detailed study and investigation into the manufacturing processes needs to be done to prepare a catalog that ties minimum order machines to a geometric feature.

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