Appendix 1: Part Evaluation

Evaluation Rationale

All real objects require space to exist and are therefore 3-dimensional in nature. Space is always defined using a 3 axis coordinate system (Cartesian, Cylindrical, or Polar)

Historically, mechanical parts are usually fully described using a series of detailed drawings. This means that a 2-dimensional (pictorial) medium is used to fully describe a 3-dimensional (spatial) object. Inherent in this process is the requirement that one of the three spatial dimensions must always remain unused. This limitation requires a one-dimensional reduction of the part results in a series of 2-dimensional drawing “views”.

Each drawing view then lies on a 2-dimensional paper surface or plane. Since the viewing direction (from the observer’s eye to the paper) is always along the third, and unused, dimension of the drawing view. This means that each drawing view is oriented normal (perpendicular) to the viewing direction. Each established view allows the use of a 2-dimensional Cartesian or Polar co-ordinate system, or some combination of the two, to fully describe the sizes and locations of every feature of the object which is aligned in that particular view. A complete set of prints requires making as many views as necessary until all features of the object have been fully described.

Manufacturing the represented part requires both positioning and motion and is therefore a spatial process. All motion is some combination of translational (linear) or rotational (angular) change. All of these changes will happen in one of three directions in space. Spatial position, or translation, can be fully described using only 3 axes. However, rotation around these three axii introduces another three degrees of freedom so a total of six degrees of freedom (or, independent variables) is required to fully describe motion in space. When a tool extension along an axis is added in, a total of 9 axii are required. As a result, industry has standardized one set of 9-axii to describe positioning and motion that occurs in the manufacturing space.

Each machine motion is described using this system and the more complex the machine, the more degrees of freedom are required to describe it and the higher its axis rating. For instance, a drill press is a simple machine used only for drilling holes. It only extends a rotating tool linearly along a single axis. The lathe is a 2-axis machine. Its tool can be positioned either linearly or radially with respect the machines axis of rotation. The vertical milling machine is a 3-axis machine. Its tool can be positioned in either of two directions of a horizontal plane as well as along the axis normal to it. Live tooling lathes and milling machines equipped with a rotary table are both 4 axis machines. The 4-axis milling machine has its original 3-axis positioning motion (x, y and z) and when a rotary table is added to allow for rotational positioning around its (fourth) axis it establishes an “a”, “b”, or “c- axis” depending on its orientation. The live tooling lathe has its original two motions (the x and z axes) but also allows a rotating tool to change its position in height (the y axis) as well as index the part in rotation (c axis). A full 5-axis milling machine has all the function of a 4-axis mill and also allows control of an additional tilting motion.

The information on the print fully describes the part as a desired final result, but, it does not describe how the part is, or should, actually be made. To turn raw stock into a finished part, it is first necessary to determine all of the machining operations required to create the parts features, the order these operations needs to be performed, and what fixtures and toolpaths will be necessary to accurately position the part during the machining operations. This is the necessary information iwhich allows the machine(s) to be set-up to make the part. With a standard (3-axis) CNC machine, every view or orientation of the part on the print will requires its own individual machine set-up to be performed and sometimes, additional setups will be required if the drawing calls for repetitive features in different orientations.

Each of these machine set-ups take time and creates another opportunity to introduce positional errors (and scrap) into the process and adds to the final cost of manufacturing the part. The economic impact of set-up costs is directly correlated with increasing part complexity and as technology progresses, it generates a need for making increasingly complex parts. Since multi-axis (more than 3) machines reduce the number of setups required while allowing the creation of parts with higher greater geometric complexities, they are becoming the industry standard and this is one factor driving the increasing need for technicians who can effectively use them.

To evaluate a part for its suitability in teaching multi-axis programming and setup skills, the project PI's and Co-PI's (PI's) first needed to define what constituted a "good" educational part. Through a process of discussion and brainstorming, the PI's identified three main characteristics that were desirable for a useable part and defined three evaluation criteria which could be used to systematically rate them.

Criteria Used In Part Evaluations

1.) Educational Versatility:
A "good" educational part should have a larger degree of "educational versatility" which means it can be used to demonstrate more than just one thing. For instance, Must the part be made on a particular machine or can the same part be used to teach students on a variety of machine types? And, if so, how many? If it is possible to make a particular part on either a 3, 4, or 5-axis machine, then a student can run the same part on all three machines in order to learn the advantages and disadvantages of each.

Setting up the same part on different machines increases learning efficiency because once the student is familiar with the part, and is familiar with its features and dimensions, no additional time is required for contemplating a new, unknown, set of goals and objectives. This approach also enhances the overall learning experience because it focuses on the differences which are the advantages and disadvantages of each machine, its capabilities and the requirements for proper fixture setups. This is exactly the type of educational experience that can provide a student with the foundational understanding and basis for determining which manufacturing techniques and methodologies will be the most cost effective and result in better choices and proper machine selections. For these reasons, the total number of machine-types on which a part can be made was used as a selection criteria.

2.) Geometric Diversity
Educational parts should have enough complexity to require the application of various concepts and techniques being taught, but they should not be so geometrically complex and challenging as to be discouraging to the student. Enough repetition should be required to adequately reinforce learning, but not so much as to create frustration or necessitate the wasting of time. Machining large numbers of repetitive features only requires a simple re-positioning of the part. These repetitive actions require additional time but do not generally add to the learning content. Therefore, a suitable part will require machining a greater variety of features rather than a greater number of them. For this reason the total

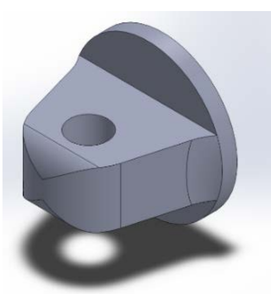
number of different surfaces, orientations, and shapes required to define a part were used as scoring criterion.

3.) Economic Feasibility.
The main purpose of an educational part is to teach new concepts and skills to untrained students. Therefore, these educational parts are expendable and, as such, it is desirable that they should only contain as much material as necessary to teach the aspects of machine programming and fixture design actually required to meet the challenges in making that part. Although industrial parts may be quite large, and demand special material handling knowledge and equipment, the size of the part is generally a matter of scale and is not a very important factor in training a multi-axis programming technician. This is because the toolpaths required to program a machine to run a smaller version of that part, and the challenges faced in holding it, remain nearly identical. The PI's therefore concluded that all parts used in a certificate program should be reduced in size as much as possible. Ideally, they should be sized so they can be made with standard sized (durable) tooling from a readily available, standard size of inexpensive stock material.

Methodology and Results

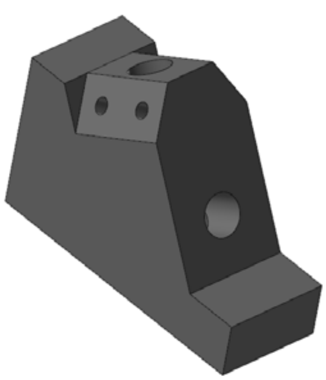
By looking online and soliciting part suggestions from industry and training partners, the PI's were able to identify 10 different prospective mechanical parts as shown below:

Engine Mount

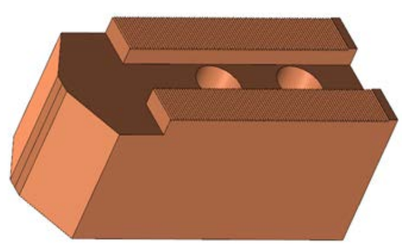


Manifold

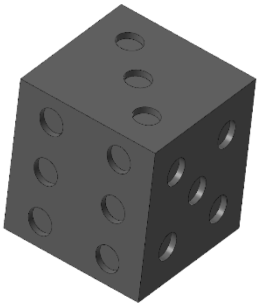
BPW4



Chuck Jaw

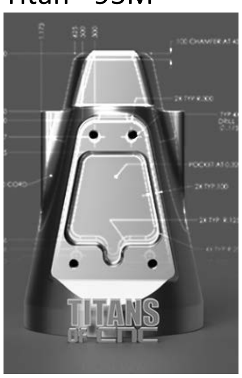


Dice

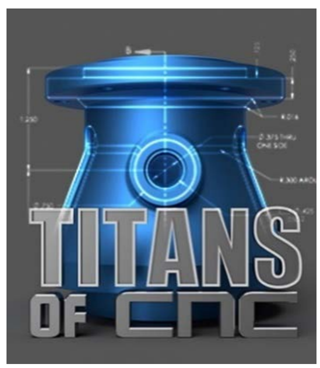


Titan -28LM

Titan - 95M

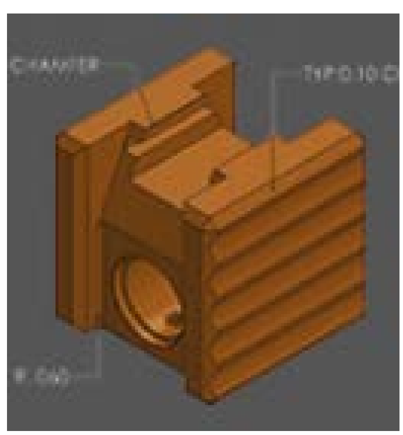


Titan 96M



Titan 97M

Titan 138M



Each of these parts has the potential of being used as a training project within an Advanced Multi-axis CNC Programing Certificate. Next, a rating rubric was created and used to evaluate each part to determine how well it met the criteria of being a "good" multi-axis training aid".

Every part was rated, in each on each of the three evaluation criteria as follows:

1.) Educational Versatility Rating (Versatility).
The evaluators first determined if a part could feasibly be made on each of the different machine types (3, 4 and 5-axis) and if so, how many setups would be required to produce it on that particular machine-type. Since it is desirable for a versatile part to be made on a large variety of machines with minimal setup time, the PI's chose to create a "Versatility Quotient" (VQ) which could be used to rank the parts. The VQ was calculated, as follows, for each part:

VQ = Total number of possible machine types which can be used to create the part/Total number of setups required to make the part on all possible machine-types.

The authors found that 5 of the parts evaluated for versatility (50%) were so complex that making them on a 3-axis machine was deemed unfeasible. There was also a 6th part (BPW4) which was not suitable for a 4-Axis machine. As such, these parts may still have great value in teaching other aspects of multi-axis programming, but would not be good choices for demonstrating the advantages of all the machine-types.

The parts which could be used on all three machine types, ranked for versatility, turned out to be:

Part Name	VQ
VU Chuck Jaw	.500
Engine Mount	.333
Dice	.273
Titan-138M	.231

The best parts for demonstrating the difference between only the multi-axis machines (no 3-axis) were:

Part Name	VQ
VU Manifold, Titan-97M	.500 (Tied)
Titan-96M, Titan-28LM	.400 (Tied)
Titan-95M	.286

And finally, although the BPW4 was found to be unsuitable for use on a 4-axis machine and it's VQ is the lowest of all, It is the one part which can best demonstrate efficiency gains available by using a 5-axis mill. This is true because on a 3-axis mill the part requires 10 setups, but this is reduced to only 2 when a 5 axis one is used.

2.) Geometric Diversity Rating (Diversity)

To determine a parts degree of geometric diversity (GD), it was necessary to rate the part based on its geometric properties. To fully describe this trait, the PI's broke each parts properties down into two categories: Geometric Forms and Geometric Orientations (GF and GO). To rate a parts richness of GF, the PI's determined the total number of sides (faces or surfaces), angles and curves required to define its features. These numbers were then summed and the total used to provide an overall score of the parts GF. So, a parts GF score is directly related to how geometrically complex that part is based on the types of features it has, and the more types of features it has, the higher it scores.

The GO of these features was also considered.
A direct correlation exists between the number of orientations required to make a part and the number of setups used in traditionally making it. If a part requires no auxiliary views it can be made using a maximum of six setup orientations (one setup for every primary view). But, any feature on a part that is not oriented orthogonally to any of the primary views, will require establishing a new (auxiliary) viewing plane. Each new auxiliary view will require that the part be held in that orientation in order to machine the features which are in that plane or orthogonal to it. If a secondary auxiliary view is required, then another (compound) re-positioning with respect to the primary auxiliary plane will become necessary, and likewise, if a tertiary auxiliary view if required, another orientation, compound to the secondary orientation will be needed. Also, if these features are duplicated around a rotational axis, then each new instance of the repetitive feature will require its own orientation.
The biggest difference in the number of setups required for these orientations occurs based on the machine type. For a 3-axis mill, the number of setups and orientations will be equal. A fourth (rotary) axis can reduce the number of setups required because it can index the part around the rotary axis into any number of new orientations without the need to add to the number of setups. And, since the first setup on a 5-axis mill can be used to tilt the part into any number of spatial orientations, this eliminates all other setups, except the last one which is required to clean up the remaining (part holding) face.

To evaluate a parts overall GO, the PI's created a score based on how many orientations would be required to hold the part to machine all of its features. This number is equivalent to the number of setups required to make the part on a 3-axis mill.

Finally, each part was assigned an overall GD score based on the following formula:

GD = GF + GO

This score was used to rank order the parts based on their degree of complexity.
Ranked from Simple to Complex, the results were:

Part Name	GD
Dice, VU Chuck Jaw	12 (Tied)
Engine Mount	15
Titan-28LM, Titan-138M	18 (Tied)
Titan-97M	19
Titan-95M	21
BPW4	24
Titan-96M	26
VU Manifold	27

Recommendations

The PI's feel that the parts selected for use in a multi-axis certificate program should progress in their degree of complexity as the curriculum advances and the students develop increased proficiency levels.

So, based on the average GD score being 19.2, and a total range of 15, the PI's assigned the parts into 3 tiers of increasing complexity ranging from Basic, through Intermediate and into Advanced.
The parts fell into the following categories in these orders:

Complexity Level	Appropriate Parts
Basic Parts (GD= 12-17)	Dice, VU Chuck Jaw and Engine Mount
Intermediate Parts (GD= 18-22)	Titan-28LM, Titan-138M, Titan-97M, Titan-95M
Advanced Parts (GD= 23-27)	BPW4, Titan-96M, VU Manifold

When ranked by VQ (highest to lowest) within these categories the list part order became:

Chuck Jaw, Engine Mount and Dice
Titan-97M, Titan-28LM, Titan-95M, Titan-138M
Manifold, Titan-96M, BPW4

This information should be helpful in selecting appropriate parts while developing course work or in assigning appropriate projects for use in the multi-axis programming curriculum which CAMP has proposed to the TCSG.

3.). Economic Feasibility

The PI's recommend that any part selected for use in a certificate program should be reduced in size as much as possible yet be large enough to be machined using standard sized (durable) tooling from a readily available inexpensive, stock material of standard size.

In searching for appropriate multi-axis parts to evaluate, the PI's found the "TITANS of CNC: Academy" (Titan) online (at http://academy.titansofcnc.com/). Titan has made a "5-Axis Series" of parts publicly available for educational use. Regarding the use of these parts, the Titan website states:

"The material called out is 6061-T6 Aluminum, and seven of eight parts can be cut from a standard 3.0 Diameter Rod."

The PI's agreed that, for educational purposes, there was really no reason to have a part of such a large size. Making a part of this scale requires a large sized (hence expensive) piece of stock and machines large enough (also more expensive) to handle it. The PI's recommend this size be reduced to substantially reduce the required machine capabilities and the cost of materials involved.

For instance, assuming the original 3" diameter part is 3" long, each original part will require about 21 cubic inches of material. If the part could be scaled down, and made from a standard 2" diameter rod, it would then be only 2" long and require 6.3 cubic inches, or 1/3rd of the original volume of material. This would yield a 66% reduction in material costs. And, if scaled to a 1" diameter size, it would be 1" long and require only about 0.8 cubic inches of material, which is less than 1/25th of that required for the 3" original which represents a whopping 96% reduction in material costs!

However, the Titans of CNC's "Terms of Use" clearly states:

"… TITANS of CNC: Academy is provided as a public service and as a resource for learning. ALL SITE CONTENT is the intellectual property of TITANS of CNC: Academy. You have the right to copy and share all materials herein in any medium or format. You may not use materials for commercial purposes and you may not modify or redistribute modified materials. We reserve the right to receive credit for all uses of Content outside of the TITANS of CNC: Academy Site. …"

This language specifically prohibits both, re-dimensioning these parts (modifying the material) into a more cost effective scale, and, disseminating (redistributing) them to the other schools. Further, Titan's desire to maintain both intellectual property, and, credit rights means that these parts are not really being made available for use in a way that is totally free of complicating legal encumbrances. Therefore, *the PI's recommend that Titan parts should not be used within the proposed certificate*. Instead, a totally new set of different and smaller parts with the types of features and numbers of orientations (level of complexity) should be created. This will insure that the proposed certificate's curriculum content is totally unencumbered and can be freely disseminated to other schools.

Additional Comments/Observations

Based on feedback provided from COMP-GA instructors who attended instructor training, there were several things that stood out as being very effective as CAMP teaching methods. The instructors all commented on how helpful it was to see the training from a "students" perspective and many were impressed by how effective the presentations were.

One significant point mentioned, was that in the training offered at both Vincennes University (VU) and RAMP at Central Maine Technical College, both provided the educational foundations in a computer lab/classroom environment. The labs were set up in a way that allowed the training facilitator to face the students while demonstrating the software. The students were all equipped with high level laptops that included upgraded, high level, graphics hardware which was specified to provide optimum performance while running the software being demonstrated.

During the class, the facilitator's computer screen was projected onto the wall, behind the facilitator, so that all the students can see what was being done in real time. This allowed each student in the class to follow along and keep up with the lesson the instructor was going through on their own computer.

After participating in this type of instruction, and seeing any relevant computer simulations that illustrated the pertinent concepts, the class and the instructor would then move out of the classroom and go to the machines. There, the class applied and implemented on the machines the lessons which had been covered in the class. The PI's recommend that the proposed TCSG multi-axis certificate be modeled around, and utilize, this style of training delivery.

Another thing that the PI's learned from their CAMP training is that they can make a significant improvement in the quality of their current CAD/CAM training. The training provided by MastercamU made it obvious that they need to modify the format of their existing curriculum to implement a teaching methodology which requires students to strictly adhere to the rigorous procedural format which MastercamU has established for their nationally recognized certification tests. By doing this, future students going through the program will simultaneously learn the specific CAD/CAM programming techniques and habits required for Mastercam certification and their pass rate on the timed certification exam should be improved, because the test format will be familiar and seem like other regular classroom or homework exercises.