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# PLM Based Digital Design Manufacturing and Process Monitoring of an Impeller Manufacturing- a Senior Project at Virginia State University

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## Abstract

Virginia State University's manufacturing program is surrounded by the industrial/research communities including Rolls-Royce, Alstom, Newport News Ship Building, and Commonwealth Center for Advanced Manufacturing (CCAM) etc. Impellers, as advanced mechanical products commonly used in turbo-machineries, are heavily investigated by these companies on design, manufacturing and inspection. An impeller consists of numbers of similar blades revolving at 360 degrees onto a hub surface. The blade consists of a suction surface, a pressure surface, a leading edge, a trailing edge and a shroud surface. Each blade is ruled surface and twisted from the leading edge to the trailing edge. Due to the design complexity of impellers, 5-axis CNC machines are the most suitable for machining impellers because of the flexibility of tool orientations that is necessary to machine the area between the twisted blades. However, 5-axis CNC machines are too expensive for many universities or industries. 3-axis CNC machines are efficient on cutting time and cost, although serious collision will occur due to the tool movement that constraint only to translations movement. Thus, integrating 3-axis for rough machining and 5-axis for finish machining could be economic to fabricate impellers. Besides this, VSU recently received a generous NX PLM (Product Life Management) software gift from Siemens. Equipping our students with skills of "Digital Design Manufacturing and Process Monitoring of an Impeller Manufacturing" will better prepare them for job market or graduate schools.

In this project, two groups of students were assigned different senior design tasks on design and manufacturing of impellers. Students in Group I design impellers using PLM's computer aided design (CAD) capability, then simulate the machining process and generate the NC code for impeller using PLM's computer aided manufacturing (CAM) capability, and then select cutting tools and cutting parameters, finally manufacturing the impeller with 3-axis and 5-axis CNC machines. Group II's task is to monitor cutting force, power consumption during the manufacturing process. Their tasks involve with sensor selection, Labview programming to integrate sensors, data collection and analysis on force and power on different machining features on impeller. Group II is also required to implement finite element analysis on the machining and fixture to simulate the strength and force response using PLM's computer aided engineering (CAE) capability. This paper details the challenges, solutions and outcomes of this senior project. The learning outcome from this project can improve several courses in manufacturing curriculum including: 1) CAD/CAM, 2) Manufacturing Processes, and 3) Manufacturing Automation etc.


## 1 Introduction

President Obama announced a $1 billion investment in a National Network for Manufacturing Innovation (NNMI) program to revamp a vibrant advanced manufacturing sector for the American economy and national security [1]. The NNMI program has the goal to advance American domestic manufacturing by creating a robust national innovation ecosystem. Virginia State University's manufacturing program is surrounded by industrial/research communities including Rolls-Royce, Alstom, Newport News Ship Building, and Commonwealth Center for Advanced Manufacturing (CCAM) etc., which partner with the Digital Manufacturing & Design Innovation (DMDII) Institute in NNMI [2]. VSU recently received a generous NX PLM (Product Life Management) gift from Siemens. NX PLM software integrates outstanding capabilities of Computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), product data management (PDM) and digital manufacturing. It is an excellent platform for companies to manage the entire lifecycle of a product from ideation, design and manufacture, through service and disposal in an efficient and cost-effective way.

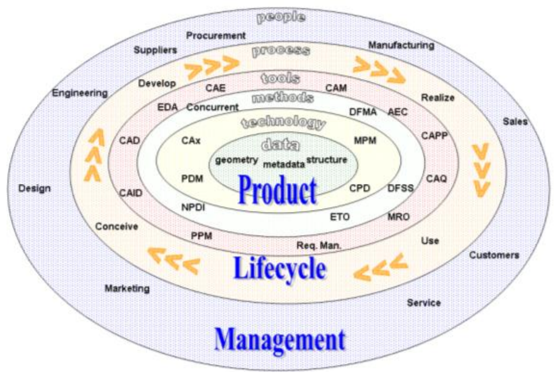



**Figure 1 Product life cycle in the PLM environment [3]**

Equipping our students with skills of "Digital Design and Manufacturing Innovation" will better prepare them for job market or graduate schools. When selecting which product as for the innovation design, impellers came to our mind. Impellers, as advanced mechanical products commonly used in turbo-machineries, are heavily investigated by the aforementioned companies on design, manufacturing and inspection. An impeller consists of numbers of similar blades revolving at 360 degrees onto a hub surface. The blade consists of a suction surface, a pressure surface, a leading edge, a trailing edge and a shroud surface. Each blade is ruled surface and twisted from the leading edge to the trailing edge. Due to the design complexity of impellers, 5-axis CNC machines are the most suitable for machining impellers because of the flexibility of tool orientations that is necessary to machine the area between the twisted blades. However, they are too expensive for many universities or industries. 3-axis CNC machines are efficient on cutting time and cost, although serious collision will occur due to the tool movement that constraint only to translations movement. Thus, integrating 3-axis for rough machining and 5-axis for finish machining could be economical of fabricating impellers.

With those in mind, Virginia State University adopted "PLM based digital design and manufacturing of impellers" as the senior design project. This project is expected to enhance the students' practical skills on digital design and manufacturing. The learning outcome from this project can improve the curriculum of 1) CAD/CAM, 2) Manufacturing Processes, and 3) Manufacturing Automation etc. This paper details the challenges, solutions and outcomes of this senior project.

The rest of this paper is organized as follows: Section 2 surveys related methods to impeller design and manufacturing. Section 3 discusses the senior design tasks on "Digital Design Manufacturing and Process Monitoring of an Impeller Manufacturing". Section 4 presents the results and outcome evaluation. Section 5 concludes the design tasks and outlines the future direction.

## 2 Literature Review

As shown in Figure 2, the centrifugal impeller is a circular revolving entity, which is composed of identical blades/splitters and a hub. The impeller blade is composed of a suction surface, a pressure surface, a leading edge and a trailing edge. The shroud surface identifies the outer shape of the blade. The surface of the blade will be closed between the shroud surface, the suction surface and the pressure surface. Rotating the shroud curve around the axis of rotation forms the shroud surface.

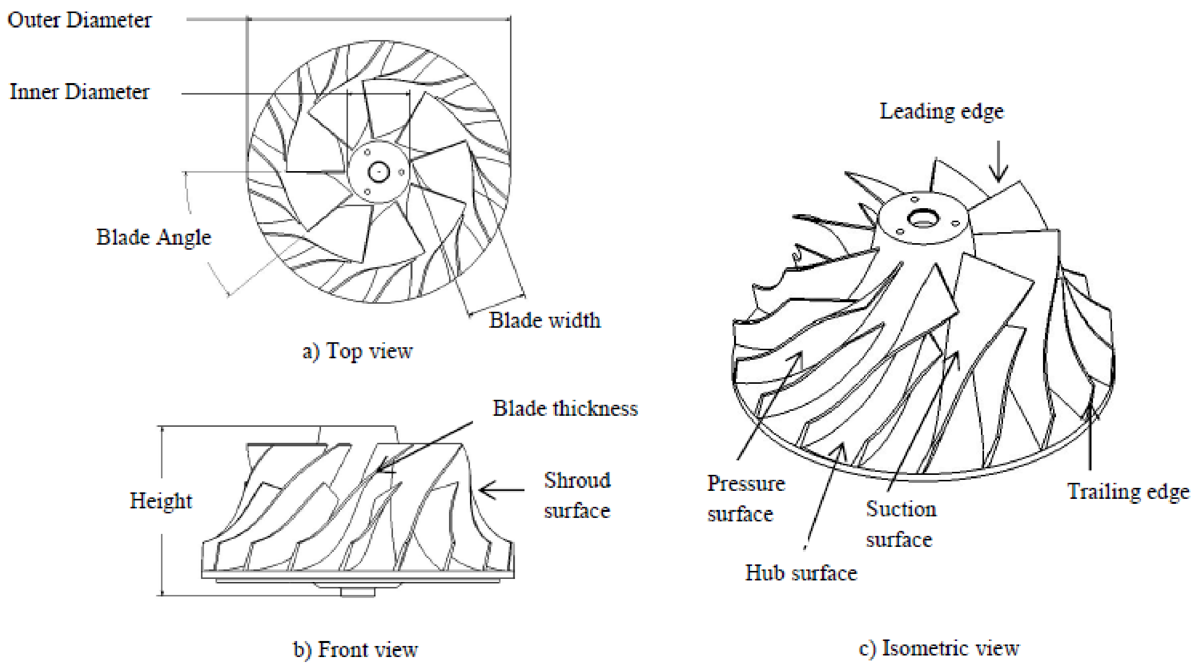



**Figure 2 Illustration of the impeller products [4]**

Impellers have the free form surface features. Impeller blades are is usually designed with a ruled surface. The impeller hub is usually designed with an irregular surface, and is machined within a narrow and deep groove. As the surface is normally twisted in design to achieve the required performance, when a 3-axis computer numerical controlled (CNC) machining center is used to cut a typical centrifugal impeller, it can cause overcut and/or collisions between the cutting tool and impeller. In this case, 5-axis machining is ideal for impeller manufacturing. However, great difficulties are expected in performing five-axis rough machining especially in the rough machining, which is recognized as the most important procedure influencing the machining efficiency and is critical for the success of the following finishing process. Chuang et al. [5] overcame the difficulty of 5-axis machining of impellers by implementing the algorithm of the constant scallop height method to improve tool-path planning of rough machining. As a result, cutting location (CL) data based on the geometry model of blade and hub of the impeller were generated. Finally, The CL data were confirmed by comparing them with original CAD model through software simulations and later by machining experiments. The results of verification proved the machining methodology and procedure to be successful [5].

Since much of the machining time is consumed in rough cutting to remove unnecessary stock materials between impeller blades, Suhaimi et al. argued that 5-axis rough machining of impellers is not efficient enough yet [4]. They first introduced a 3-axis machining strategy that removes as much material as possible from the areas between blades. This 3-axis machining strategy presented an efficient rough-cutting strategy for machining a centrifugal impeller. They achieved 19% of total machining time reduction by using the 3-axis rough machining. For further improvement, they studied an improved 3-axis machining strategy by applying feed-rate scheduling for more efficient rough cutting. Because there are two types of feed rate scheduling, namely, cutting force and material removal rate based scheduling. Their work focused on cutting force based feed-rate scheduling to increase the feed-rate onto an allowable level. Current research in feed-rate scheduling applies cutting force calculations for each cutter-workpiece engagement, experimenting with different depth-of-cut layers. They calculated cutting force for each cutter-workpiece engagement by employing a finite element method. Cutting tool and workpiece geometry was meshed and analyzed to find out best feed-rate scheduling. The rest of material left from the 3-axis machining would be removed by 5-axis machining. Their results showed that this hybrid roughing strategy, namely, 3-axis machining with feed-rate scheduling and 5-axis machining, could reduce total rough machining time significantly up to 43% [4].

## 3. Planned Senior Design Project

In our senior project of designing and manufacturing impellers, two groups of students were assigned different senior design tasks. Students in Group I design impellers using PLM's CAD capability, then simulate the machining process and generate the NC code for impellers using PLM's CAM capability, then select cutting tools and cutting parameters, finally manufacturing impellers with 3-Axis and 5-Axis CNC machines. Group II's task is to monitor cutting force, power consumption during the manufacturing processes. Their tasks involves with sensor selection, Labview programming to integrate sensors, data collection and analysis on force and power on different machining features on impeller. Group II is also required to implement finite element analysis on the machining and fixture to simulate the strength and force response using PLM's CAE capability. The review feedback on our abstract submission to ASEE 2015 suggests "separating the two groups' work into different papers for more detail discussions." We think that suggestion is invaluable, so we only focus on the description of the first group's work on digital design and manufacturing of impellers.

The design tasks will be implemented in two semesters in the MANE 461/462-Senior Design I/II respectively. In MANE 461-Senior Project I, students are expected to "solve typical of problems that graduates encounter in their professions and which involve costs, planning scheduling and research. Formal written reports suitable for reference library, that include discussions of methodology, results, and conclusions" [6]. In MANE 462- Senior Project II, students are expected "to implement appropriate manufacturing process, toll, computer control, quality knowledge, and societal considerations to solve a mix of industry and in-house structured group projects. Projects will progress through a complete manufacturing cycle from design through implementation." [6]

In Senior Design I, the tasks are scheduled in three stages.

1. Project definition phase:

This phase constitutes defining the design problem, understanding its significance and relevant factors. At the end of phase 1, the students are required to submit project definition report, which will describe the current practice of the problem they are going to solve, clearly identify the gap between customer needs and existing designs, its significance, and potential influencing factors etc.

2. Concept design phase:

This phase involves collecting, analyzing data, improving understanding of the relevant factors, and finalizing the concept and/or experiment design. At the end of phase 2, the students are required to submit concept design report, which will describe the data collected, preliminary analysis, and generate concept design based on the gap you identified in Phase 1.

3. Prototype design phase:

This phase involves summarizing the findings in the previous two phases, and finalizes the proposed design strategy, and presents the proposal publicly. Prototype report is required at the end of phase 3, which must be a comprehensive and self-contained report. This report will be regarded as a "contract" and plans for the Senior Project II. A reader must be able to get a complete picture of the problem and the solution to the problem.

Each report has an associated class presentation. It is required that each group member presents a significant portion in his/her group presentation. The presentation should be prepared to defend the project's assumptions, methods, solutions, and question answering. A clear and concise presentation of the solution and insight into the problem are primarily important, and strict time limits will be imposed.

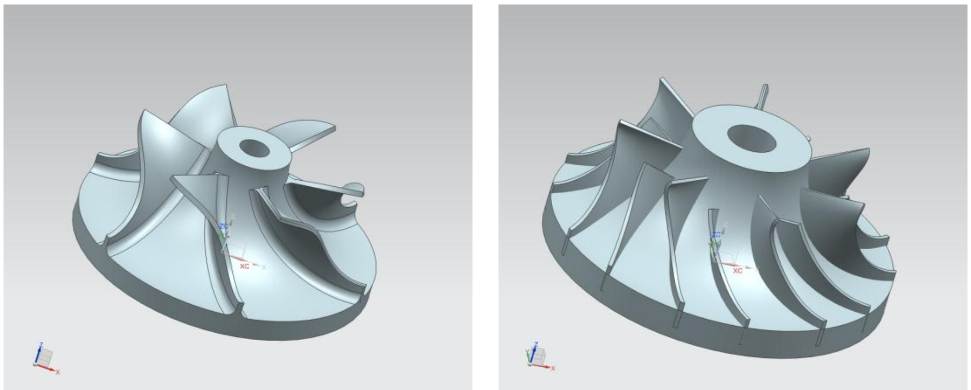
## 4 Progress and Outcome evaluation and analysis

### 4.1 Phase 1 Definition Outcome

At the beginning of the class, students were directed to understand the importance and currency of this project through literature reading, video watching-"Rolls Royce-How to Build a Jumbo Jet Engine" (https://www.youtube.com/watch?v=VfomloUg2Gw ), plant tour to Rolls Royce, and class presentations.

### 4.2 Phase 2 Design Outcome

When the students were studying the "CAD/CAM" classes, the software that they learned were Solidworks and MaterCAM. VSU manufacturing program adapted the NX PLM software in Fall 2014, so the first step in this senior design is to train the students using the PLM's CAD functions. They were given different training sections in the textbook of "Parametric Modeling with NX 9" [7], also using the training materials on youtube. To evaluate their learning outcome, at the end of this phase, they were requested to submit the design documents and prototype of designed impellers. The impellers from the two design groups are shown in Figure 3. In Figure 3(a), the impeller has no splitters; while in (b), splitters are included in the design. For this senior project, the focus more concentrates on the manufacturing and inspection of the impellers. The students were only required to design the impeller with 6 blades (and 6 splitters) using the free form modeling capabilities of PLM, the blades dimensions were specified by students with the only constraint on the feed stock material size, which is a cylinder with diameter of 7 inches, and height of 3 inches. We will improve the design process in the future with optimizing the dimensions, shapes etc. of the blades, using the knowledge of fluid mechanics, strength of material, and finite element analysis.



(a) (b)

**Figure 3 Designed impellers by the students**

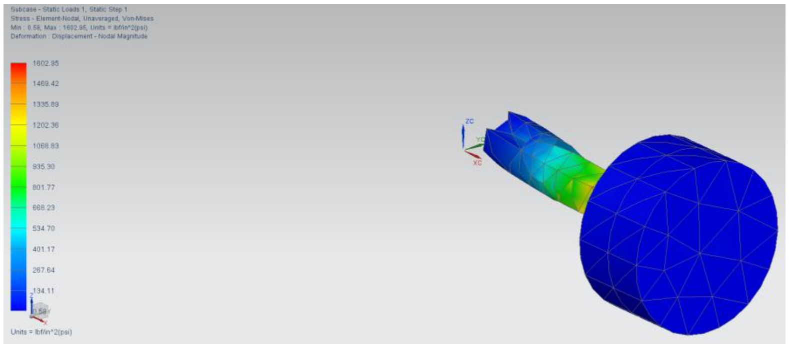
The designed impeller CAD files were converted into STereoLithography (STL) files to 3D-print prototypes. The printed prototypes are illustrated in the Figure 4. These two prototype products successfully conclude the chapter of product design. The students were also excited to see that their designs in paper become the real prototypes. It greatly stimulated their interests into the senior projects, also strengthened their confidence to achieve the design tasks on the next stages.

**Figure 4 Prototype products from the two groups**

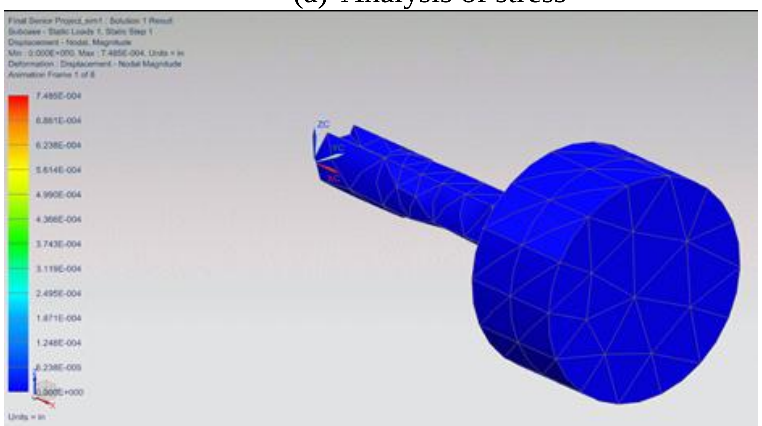
### 4.3 Fixture Design and Analysis

Because the impellers is too large for the chuck on the CNC machines (Haas SL 10 and Haas Mini Mill), students designed a machining fixture with NX-CAD, then uses NX-CAE to analyze the possible stress and the displacement of the fixture in the machining process. The CAE analysis results are shown in the Figure 5. Finally, the fixture was fabricated as in the Figure 6.

The feed stock material will be mounted on the shoulder of fixture, and then tightened to the fixture with a screw, a bolt, and a lock washer.



(a) Analysis of stress



(b) Analysis of displacement

**Figure 5 CAE analysis of the fixture**

**Figure 6 the fabricated fixture**

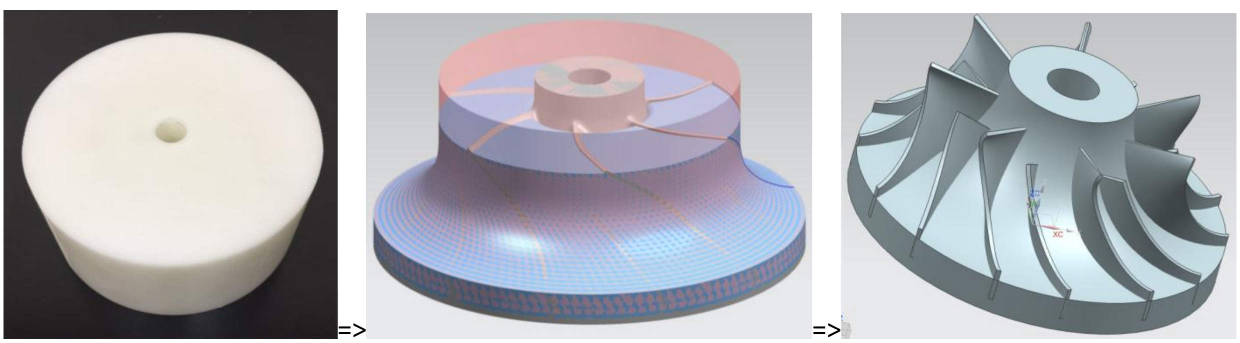
### 4.4 Phase 3 Prototype Outcomes

The complete manufacturing process of a centrifugal impeller includes shroud surface turning, hub surface rough milling, blade flank milling, and hub surface fine milling. The following section details each machining step and the results of machining. Machining simulation is also illustrated in this section.

As shown in Figure 7, the outer profile of the shroud surface of the impeller is first machined by CNC turning. After turning is completed, rough milling will proceed on the hub surface between the two blades. Rough milling on the hub surface produces a rough profile of the impeller. The general machining procedures usually include rough milling and finish milling. Operations that will machine the part include:

1. Rough the blades and splitters
2. Finish the blades
3. Finish the splitters
4. Finish the hub
5. Finish the blade blends
6. Finish the splitter blends

The rough tool path was obtained from the tool path of flank milling at certain angular interval around the axis of rotation between blades. Meanwhile, the tool tip position would be moved away from the hub surface along the tool axis to provide the fine milling allowance. The remaining material would be removed when hub surface fine milling takes place.




(a) Stock material (b) Shroud surface after turning (c) Finally machined impeller

**Figure 7. Process planning of the machining process**

**Rough the blades and splitters**

A blade includes a pressure surface, a suction surface, a leading edge, and a trailing edge. A blade is a thin component, especially the leading edge. If the normal machining procedure is adopted on the leading edge of blade, the leading edge would be easily damaged because of potential machine vibration. If the leading edge is machined first, it would keep more material in the blade to maintain the strength of the blade. This procedure substantially reduces the damage caused by vibration. The leading edge of the blade was machined prior to fine milling of the blade surface. The sequence of machining was to machine the pressure surface of the blade from the lower part towards the upper part, and then to proceed to machine the suction surface of the blade from the upper part towards the lower part. This sequence should use down-milling to minimize the effect of vibration. The operation roughs the blades and splitters using multiple cut levels and extends the tool path radially to cut the entire hub.

The cutting tool selected for roughing the blades and splitters is Sandvik ball mill with 7mm diameter. On the cut levels, "offsets from Hub" [8] was selected as the depth mode, and 100% of the tool diameter is for the offset distance. The machining section was divided into upper and lower subsections, and the upper subsection was machined first. The first tool path used the right boundary of the machining section and the constant scallop height method was used to control the desired feed between each tool path from the right to the left. The tool path was then linked in a Zig-Zag style. The machining Sequence on the hub is shown in Figure 8.

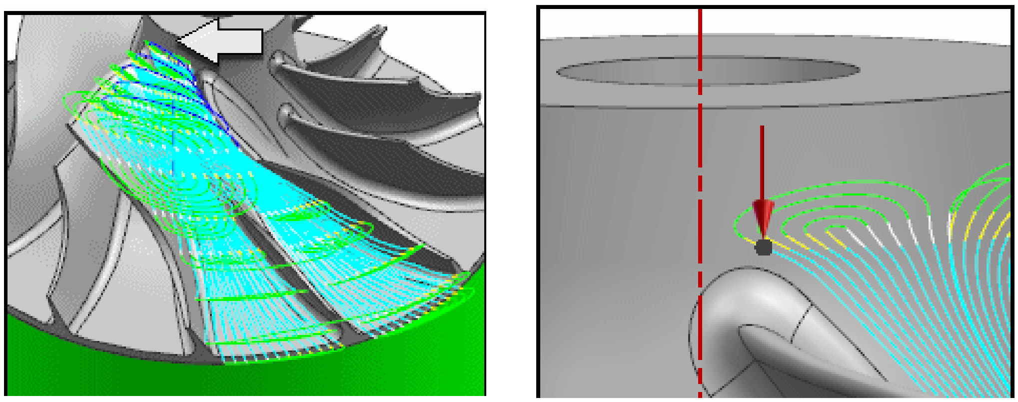


**Figure 8 Machining sequence on the hub**

The complete machining tool path on roughing the blades and splitters is shown in Figure 9. It can clearly show the difference between the wide geometrical shape and the narrow one on the hub surface and that there is no overlap on each tool path.

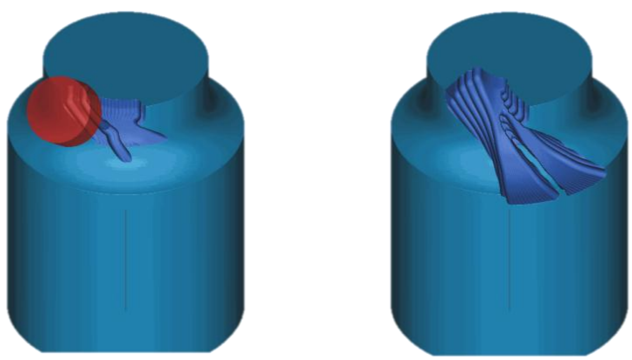


**Figure 9 Rough cut simulation on the blades and splitters**

**Finish the blades and splitters**

Following operation finishes the blades and splitters using multiple cut levels. On the cut level, "Interpolate from Shroud to Hub" [8] was selected as the "Depth Mode", the constant scallop-height of 0.05mm was used as cutting depth to plan the tool path for finish milling on the hub surface. The cutting pattern was similar to roughing the blades and splitters. The complete machining tool path on roughing the blades and splitters is shown in Figures 10 and 11.

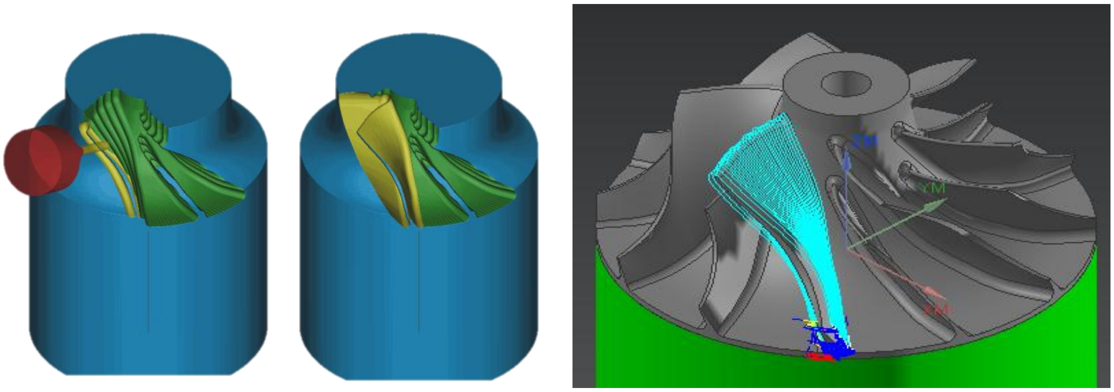


**Figure 10 Finish cut simulation on the blades**

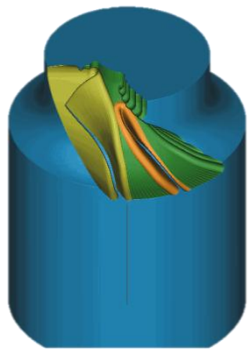


**Figure 11 Finish cut simulation on the splitters**

**Finish the hub**

This operation finishes the hub and extends the tool path at the leading and trailing edge to cut the entire hub. It uses the cutting tool of Sandvik ball mill with 7mm diameter. The tool path was extended to the upper section of the hub to finish cut this area first. Later the operation was improved by altering the tool path specifying a "Zig-Zag with lifts" [8] cut pattern to reduce the number of engages and retracts. The simulation of finish machining on the hub is shown in Figure 12.

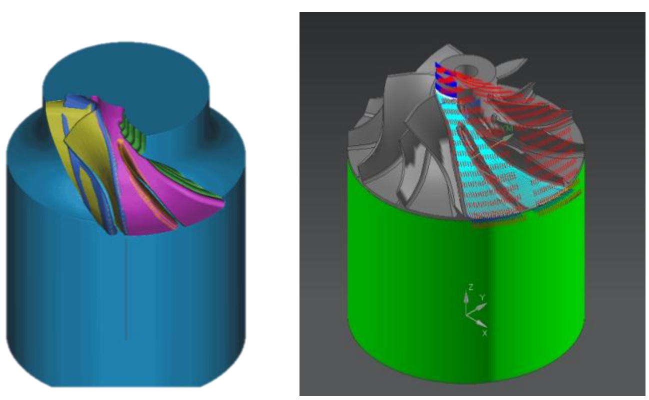


**Figure 12 Finish cut simulation on the hub**

**Finish the blades and blends**
These steps specify the operation type and groups used to finish the blade blends. It uses the cutting tool of Sandvik ball mill with 4mm diameter. On the cutting stepover, the 0.01mm was used as maximum scallop height to plan the tool path to finish the blends. The simulation of finish machining on the blades and blends is shown in Figure 13.

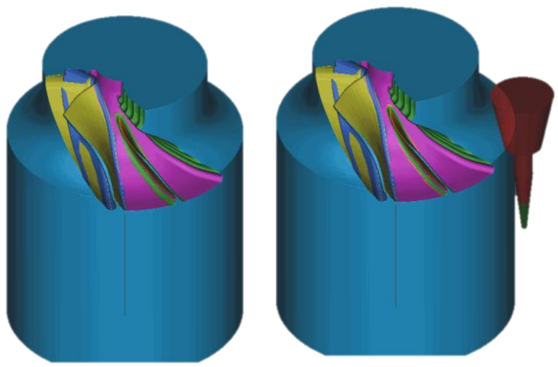


**Figure 13 Finish cut simulation on the splitter blends**

Finally the machining program sheet is shown at the bottom of this paper. This sheet was generated based on an object selected in the Operation Navigator. If the selected object is a group, then all objects inside the group are processed. If the selected object is an operation, then only the operation is processed. From the sheet, we estimate that the total machining time is around 181.33 minutes. The machining process is faster than 3D printing of impellers. For the 3D models in Figure 4, it took more than 7 hours to print it out.

**4.5 Outcome evaluation**
Students' evaluation on the course outcome is summarized as Table 1. The items (1a-14) in this table were generated from the Accreditation Board for Engineering and Technology (ABET) program outcome. The lowest grading is 1, which means the least help to students through this course; the highest grading is 5, which means the greatest help to students through this course. Five students were taking the senior project and four of them finished evaluations. Their grading on each item are listed in the columns of S1 (Student 1) to S4 (Student 4). The last column is the average scores on each item. From the evaluation, the students feel that they were strengthened greatly in most outcomes with the least grade of 3.75. Items of 1a (mathematic skills), 1b (physics and chemistry skills), 8(upstanding of global and societal context) and 10 (understanding of contemporary issues) have the grades of smaller or equal than 3.5. However, these four items are not the focus of the senior project.

The senior project also has been producing fruitful outcomes in training students' participation in research. Students delivered posters and presentations on different seminars including the Virginia Academy of Science (VAS) Fall Undergraduate Research Meeting 2014 (shown in Figure 14), National Science Foundation-Louis Stokes Alliance for Minority Participation (NSF-LSAMP) Undergraduate Research Conference 2014, and Emerging Researchers National Conference in STEM (ERN) 2015. Through research participation and seminar presentations, students were exposed to the frontier of manufacturing research. The gained experience has greatly inspired them to pursue manufacturing careers.

**Table 1 Students' scorings on the course outcome**

| | S1 | S2 | S3 | S4 | Ave. |
|---|---|---|---|---|---|
| 1a. This course improved my mathematical skills in solving engineering problems. | 2 | 3 | 4 | 3 | 3 |
| 1b. This course enhanced my understanding in physics and/or chemistry. | 2 | 3 | 2 | 3 | 2.5 |
| 1c. This course improved my engineering skills in solving problems. | 3 | 4 | 4 | 5 | 4 |
| 2. This course improved my ability to analyze problems by designing and conducting experiments. | 5 | 4 | 5 | 4 | 4.5 |
| 3. This course improved my proficiency in designing of products, equipments, tooling and /or environment for manufacturing systems. | 5 | 4 | 5 | 3 | 4.25 |
| 4. This course enhanced my competency to function effectively in a team. | 5 | 4 | 5 | 5 | 4.75 |
| 5. This course improved my ability to identify, formulate, and solve engineering problems. | 4 | 4 | 5 | 5 | 4.5 |
| 6. This course improved my understanding of engineering profession ethical responsibility. | 5 | 4 | 5 | 4 | 4.5 |
| 7. This course helped me to communicate more effectively. | 5 | 4 | 4 | 3 | 4 |
| 8. This course enabled me to recognize the importance of the impact of engineering solutions in global and societal context. | 2 | 0 | 4 | 3 | 2.25 |
| 9. This course helped me recognize the importance of engaging in life-long learning. | 5 | 4 | 5 | 4 | 4.5 |
| 10. This course improved my understanding of contemporary issues. | 5 | 3 | 2 | 4 | 3.5 |
| 11. This course enhanced my ability in using the techniques, skills, and modern engineering tools necessary for engineering practice. | 5 | 4 | 5 | 5 | 4.75 |
| 12. This course improved my understanding of behavior and properties of materials as they are altered and influenced by manufacturing processes. | 5 | 4 | 5 | 5 | 4.75 |
| 13. This course enhanced my ability to use statistical and calculus based method to analyze and control manufacturing operations. | 3 | 4 | 5 | 3 | 3.75 |
| 14. This course improved my competence in measure of manufacturing process variables in a manufacturing laboratory and make technical inference about the process. | 5 | 4 | 5 | 5 | 4.75 |

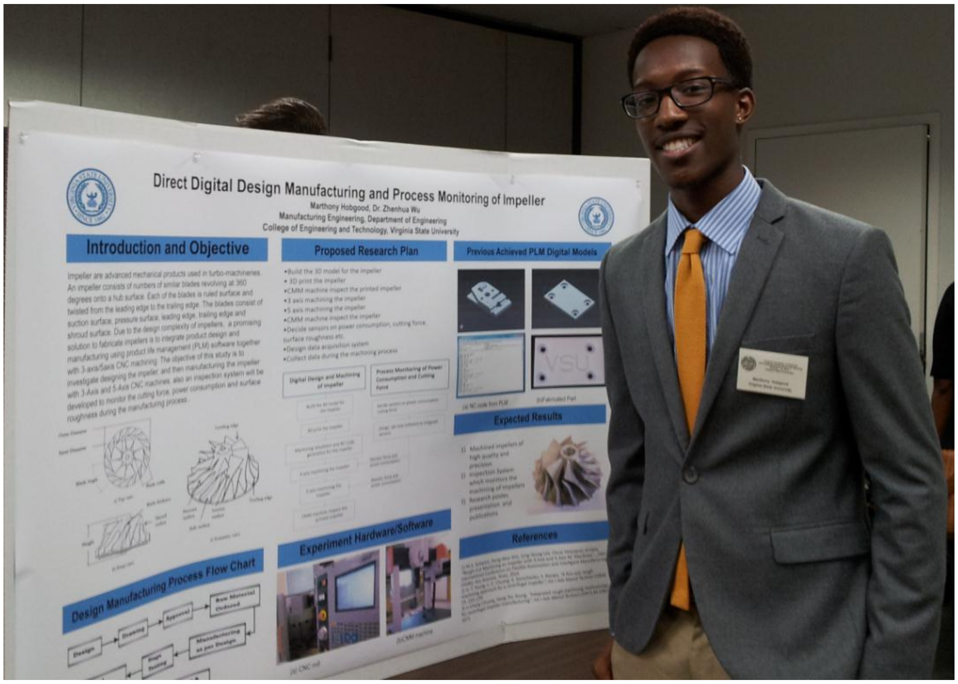



**Figure 14 Student presenting project progress on VAS undergraduate research conference**

The learning outcome from this project will continue to improve the courses of 1) CAD/CAM, 2) Manufacturing Processes, and 3) Manufacturing Automation etc. Previously, CAD/CAM class at VSU was using Solidworks and Matercam for student training. Although Solidworks owns a large portion of school users with its simplicity on CAD education and learning, it cannot support the integration of CAD/CAM/CAE, while NX has the capability. Solidworks is not the current applications for many industries including Rolls-Royce, Alstom, and Newport News Ship Building. This project enriched the VSU's curriculum of CAD/CAM on laboratory settings, experiments, and also better prepared the students' readiness for job market. The process monitoring part of this senior project tightly links the "Manufacturing Processes" and "Manufacturing Automation", students learn how to apply sensors and design data acquisition systems to monitor a real manufacturing process. The designed data acquisition system and sensory monitoring approaches can be applied to the laboratory apparatus both "Manufacturing Processes" and "Manufacturing Automation".

## 5 Conclusion and future direction

This project is phased in two semesters. Tasks in the Fall semester required the students to design the prototype of impellers, and machining simulation. From the class evaluation, students' conference posters and presentations, we conclude that they have successfully delivered all the required tasks in the Fall semester. The learning outcomes have been broadly disseminated through the students' participation in many conferences.

In the Spring semester, they will implement and improve the prototype. We already received the willingness to participate this project: Sandvik will donate us cutting tools, their technique manager will come to school to give seminars about cutting tools and impeller manufacturing processes; CCAM can provide five-axis CNC facility and technician support. We are looking forward to share the completed achievements on ASEE annual conference.

For the future directions, several ideas are: 1) Broaden the participation of industries. This project basically is an in-house project; the idea came from a conference presentation. Although we received support from industry, we should further strengthen the link with industry to make such a practice to be an industry sponsored project. 2) Further automate the manufacturing process. We have an excellent computer integrated manufacturing (CIM) system in the department, which is composed of an automated inventory, a CNC lathe, a CNC mill, an inspection station, an automated conveyor, three robotics and four computers (one master and three slaves). The manufacturing automation of impellers can be an excellent application for that CIM system.

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## Acknowledgement

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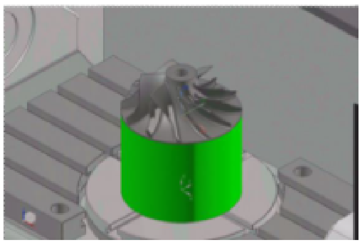
## Appendix I. Process planning sheet generated by NX PLM

# Program Sheet

| Part name: | turbomachinery_setup_1 | Drawing name: | "--" |
|---|---|---|---|
| Unit: | MM | Part number: | "--" |
| Pictures :  | | Description : | |

| Index | Operation Name | Type | Program | Machine Mode | Tool Name | Tool Path Time in Minutes | Path Image |
|---|---|---|---|---|---|---|---|
| 1 | MULTI_BLADE_ROUGH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_7 | 54.79356436819 |  |
| 2 | BLADE_FINISH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_7 | 48.31404781461 |  |
| 3 | SPLITTER_FINISH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_7 | 33.05590539000 |  |
| 4 | HUB_FINISH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_7 | 24.56479906669 |  |

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SIEMENS

# Program Sheet

| Index | Operation Name | Type | Program | Machine Mode | Tool Name | Tool Path Time in Minutes | Path Image |
|---|---|---|---|---|---|---|---|
| 5 | BLEND_FINISH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_4_6 | 10.93480550666 |  |
| 6 | SPLITTER_BLEND_FINISH | Variable-axis Surface Contouring | 1234 | MILL | BALL_MILL_4_6 | 9.695962545753 |  |

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**Appendix II. a student evaluation sample on the senior project**

**Student Evaluation Sheet for Program Outcomes**

**Couse Name: Senior Project**

Please identify your level of agreement with following statements.

| | Highest | | | | Lowest |
|---|---|---|---|---|---|
| 1a. This course improved my mathematical skills in solving engineering problems. | 5 | 4 | 3 | (2) | 1 |
| 1b. This course enhanced my understanding in physics and/or chemistry. | 5 | 4 | 3 | (2) | 1 |
| 1c. This course improved my engineering skills in solving problems. | 5 | 4 | (3) | 2 | 1 |
| 2. This course improved my ability to analyze problems by designing and conducting experiments. | (5) | 4 | 3 | 2 | 1 |
| 3. This course improved my proficiency in designing of products, equipments, tooling and /or environment for manufacturing systems. | (5) | 4 | 3 | 2 | 1 |
| 4. This course enhanced my competency to function effectively in a team. | (5) | 4 | 3 | 2 | 1 |
| 5. This course improved my ability to identify, formulate, and solve engineering problems. | 5 | (4) | 3 | 2 | 1 |
| 6. This course improved my understanding of engineering profession ethical responsibility. | (5) | 4 | 3 | 2 | 1 |
| 7. This course helped me to communicate more effectively. | (5) | 4 | 3 | 2 | 1 |
| 8. This course enabled me to recognize the importance of the impact of engineering solutions in global and societal context. | 5 | 4 | 3 | (2) | 1 |
| 9. This course helped me recognize the importance of engaging in life-long learning. | (5) | 4 | 3 | 2 | 1 |
| 10. This course improved my understanding of contemporary issues. | (5) | 4 | 3 | 2 | 1 |
| 11. This course enhanced my ability in using the techniques, skills, and modern engineering tools necessary for engineering practice. | (5) | 4 | 3 | 2 | 1 |
| 12. This course improved my understanding of behavior and properties of materials as they are altered and influenced by manufacturing processes. | (5) | 4 | 3 | 2 | 1 |
| 13. This course enhanced my ability to use statistical and calculus based method to analyze and control manufacturing operations. | 5 | 4 | (3) | 2 | 1 |
| 14. This course improved my competence in measure of manufacturing process variables in a manufacturing laboratory and make technical inference about the process. | (5) | 4 | 3 | 2 | 1 |

**Comments (Please write down your suggestion on improving this course):**

I enjoyed the designing portion of this course, it has really gave me more knowledge when it comes to designing and the different programs.