# A Novel Robotic Manufacturing System for Learning Innovation

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## Abstract

U.S. manufacturing requires speed to market to gain an advantage in global competitiveness. We propose a novel robotic manufacturing system to prepare students to deal with such a challenge by improving their learning experience in manufacturing. This is an initiative to promote the transformation of student learning experience in the manufacturing engineering technology program in the School of Engineering Technology at Purdue University. The robotic manufacturing system supports various applications of digital manufacturing by integrating both traditional subtractive manufacturing approaches and emerging additive manufacturing ones (e.g., 3D printing) in a novel way. Such a multi- functional robotic manufacturing system makes it a perfect platform for students not only to creatively learn and apply all kinds of existing manufacturing technologies, but also to actively explore new and better solutions for manufacturing problems in their team- based interdisciplinary undergraduate research. With such an innovative learning experience, students will graduate with competency in solving real-world manufacturing problems currently facing enterprises and developing future manufacturing solutions that can impact our society.

## Introduction

Robotics and automation are expected to reduce the use of humans initially, then it would lead to an overall growth in jobs in the following years based on a research entitled “Positive Impact of Industrial Robots on Employment”[1]. In 2011, there are 4 to 6 million of jobs that are directly created due to the implementation of robotics technologies according to the International Federation of Robotics (IFR)[2]. This number becomes 8 to 10 million if the indirect employments are taken into account. Due to the rapid growth of the manufacturing industry that requires speed to market to gain an advantage in global competitiveness, it is important for educational institutions to develop and offer appropriate courses and training platforms to prepare our future workforce. This motivates us to develop a novel robotic manufacturing system to prepare students to deal with challenges in the manufacturing industry by improving their learning experience in manufacturing. This is an initiative to promote the transformation of student learning experience in the manufacturing engineering technology program in the School of Engineering Technology at Purdue University.

Traditional CNC machining courses have been static for many years. As new manufacturing paradigm coming to market, it would have an influence on the previously existing systems and even change the current producing processes. Thus, engineering students should benefit by acquiring knowledge of new manufacturing technologies as soon as possible. Recently, additive manufacturing (AM) is regarded as a new industrial revolution. It allows engineers to design products without the need for tooling and fixtures during manufacturing[3]. Compared with the traditional manufacturing approaches, AM technologies have three main advantages, namely, energy and resource saving, supply chain simplification, and environment-friendliness[4]. Hence, AM technologies have the potential to be widely used to produce parts with complex geometries for both academic and various industry sectors. However, AM technologies also show several obvious limitations, such as material limits, long production time, and low accuracy and rough surface finish[5]. Instead, CNC machining technology has solved these problems by improving the machining accuracy and surface finish of a part. At present, it is a challenge to combine both AM and CNC technologies and form an optimal solution to produce parts with desirable accuracy in a short time.

In order to learn manufacturing technologies in a more comprehensive and panoramic view, students are expected to not only acknowledge the difference of various processing techniques but also be able to utilize the consolidated advantages of these techniques and explore new methods and approaches during learning. There already exist many researches focusing on the conventional CNC machining and AM processes, but it lacks investigating the integration of CNC machining and AM technologies to optimize production processes. In this paper, we present a novel robotic manufacturing system designed to meet this challenge in learning and encourage students to delve into the manufacturing processes by themselves. The robotic manufacturing system supports various applications of digital manufacturing by integrating both traditional subtractive manufacturing approaches (e.g., CNC machining) and emerging additive manufacturing ones (e.g., 3D printing) in a novel way. Such a multi- functional robotic manufacturing system makes it a perfect platform for students not only to creatively learn and apply all kinds of existing manufacturing technologies, but also to actively explore new and better solutions for manufacturing problems in their team- based interdisciplinary undergraduate research. With such an innovative learning experience, students will graduate with competency in solving real- world manufacturing problems currently facing enterprises and developing future manufacturing solutions that can impact our society.

## Literature Review

Several researchers have discussed the combination of additive and subtractive manufacturing technologies. Kerbrat et al. evaluated the manufacturability of a product and then divided it into different parts[6], as shown in Fig. 1. For the parts that have complex geometries, additive manufacturing is likely to be used to save time and energy. Zhu et al. developed an iAtractive framework that contains three processes, namely, additive process, subtractive process, and inspection process[7]. It provides an intelligent solution to manufacture products that have internal features. Besides, the inspection process provides feedback to improve the previous decision. Newman et al. proposed a Re-Plan process planning based on the iAtractive framework[8].

Using a robotic arm for 3D printing of large objects is a potential solution for integrating subtractive and additive manufacturing. The robotic arm used in a manufacturing system in has six degrees-of-freedom and can fabricate into multiple projections in each layer[9]. Mostafavi et al.

presented a materially informed Design-to-Robotic-Production process for achieving architecture application[10]. David Scheltema introduced a KUKA robotic arm to produce the micro-structure of a spider's silk thread[11], as shown in Fig 2. The previous work inspires us to bring this kind of hybrid manufacturing platform into classes to train students.

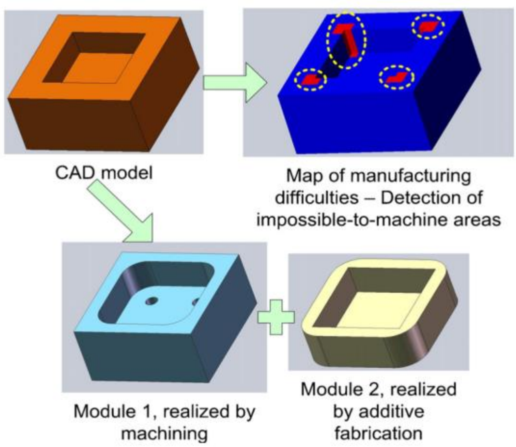


**Fig. 1**. Hybrid approach in reducing manufacturing difficulties[6].

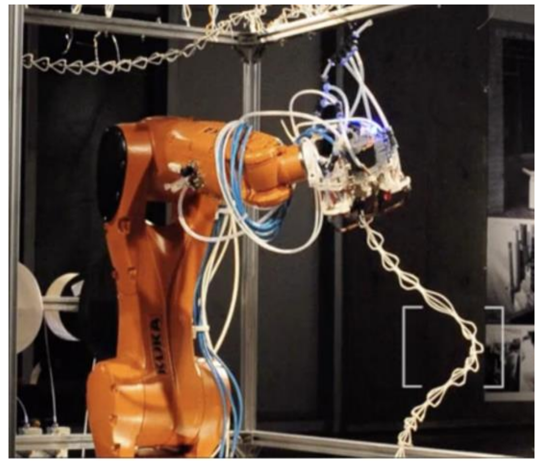

**Fig. 2**. Spider web produced by a robotic-arm-based 3D printer[11].

## System Principles and Features

The proposed hybrid robotic manufacturing system is introduced in the following sub-sections.

*Robotic Arm:*

KUKA robotic arms have been widely applied in the manufacturing industry due to their high repeatability and accuracy. In this project, we employ a KUKA KR10R1100 SIXX arm shown in Fig. 3 as our target tool such that what students practice with in class is likely the same as what they work on in their job. The maximum payload of the robotic arm is 10 kg, which meets the general requirements of the subtractive process for woods and plastics[12]. The maximum reach of the robotic arm is 1101 mm. Compact size makes it possible to be put in the lab and reduces safety problems. This robotic arm also provides compressor air ports for quick tool change. In this way, we can integrate additive manufacturing tools with subtractive manufacturing tools using a quick tool changer.

*3D Printing:*

Parts of the 3D printer is shown in Fig. 4. An Arduino MEGA 2560 and a RepRap board is used to control the 3D printer. The printing head contains a heater and a step motor, which are uniquely programmed using Arduino software. In other words, the speed and temperature of the extruder can be adjusted by the operator to meet specified needs. Also, there are fans attached to the front of the printing head to cool down the material immediately. The 3D printer is installed at the end of the robotic arm through an adapter part. The robotic arm is controlled to generate the proper trajectory of the extruder to print a part. Such a design provides many opportunities for students to program and design their own printing standards.

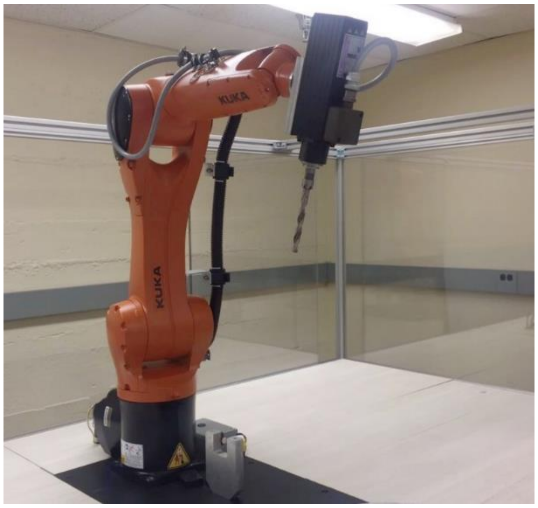

Fig. 3. KUKA robot with spindle installed.

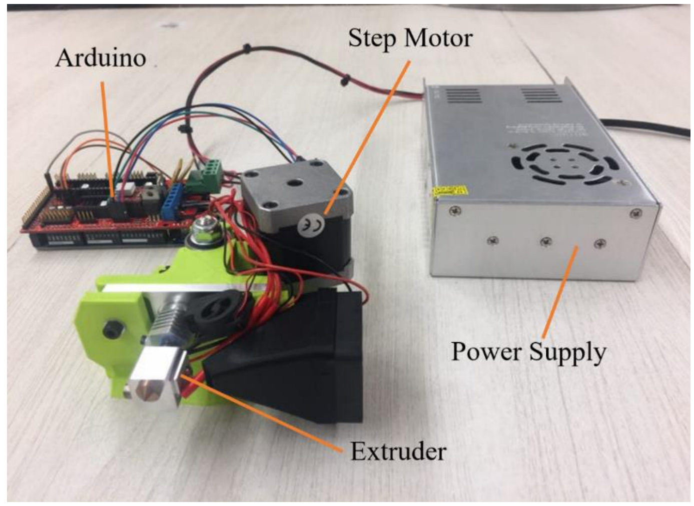


Fig. 4. End-effector for 3D printing.

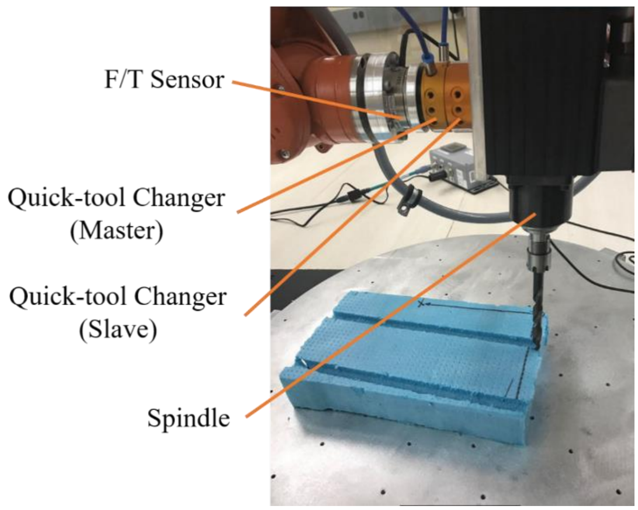


Fig. 5. Subtractive manufacturing system.

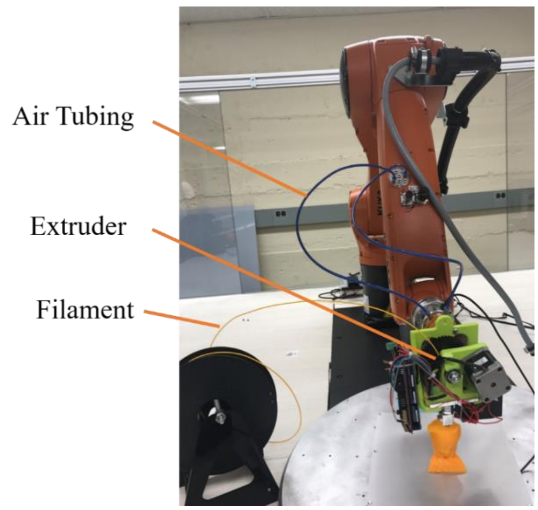


Fig. 6. Additive manufacturing system.

*End-Effectors:*
The end-effector of a robotic arm is a tool designed to interact with the environment. It consists of a gripper or a tool for various purposes such as machining, welding, painting, etc.
There are two end-effectors in this system, namely, a spindle for subtractive manufacturing and an extruder for 3D printing. Students can use a quick tool changer to switch the end effectors during the manufacturing process to achieve various manufacturing operations continuously without manually setting up the tool each time. In this way, students can have a better understanding of the advantages and disadvantages of both additive and subtractive manufacturing technologies.

The integrated subtractive manufacturing system is shown in Fig. 5. The speed of the spindle is controlled by its own controller while the spindle moves together with the robotic arm that is controlled by the robot controller. A force/torque sensor is integrated between the spindle and the robotic arm to measure manufacturing forces. The integrated additive manufacturing system is shown in Fig. 6. The temperature and feeding rate of the 3D printing extruder is controlled by Arduino while the 3D printing extruder moves together with the robotic arm that is controlled by the robot controller. The quick tool changer allows switching between subtractive and additive manufacturing conveniently.

*System Integration:*
After assembly, this hybrid robotic manufacturing system can work as either a CNC machine or a 3D printer. Students are able to control the system to achieve various manufacturing-related projects. The diagram of the system is shown in Fig. 7. Both the spindle and the extruder can be mounted on the robotic arm for subtractive and additive manufacturing, respectively. The speed of the spindle is controlled by its controller which can communicate with the robot controller. The position of the spindle is solely controlled via the robotic arm. The temperature and feed speed of the extruder are controlled by its Arduino controller which can also communicate with the robot controller. The position of the extruder is solely controlled via the robotic arm. A computer is connected to the robot controller via an Ethernet cable. Students can design parts, simulate and control the motion of the robotic arm, and create robot programs from the computer.

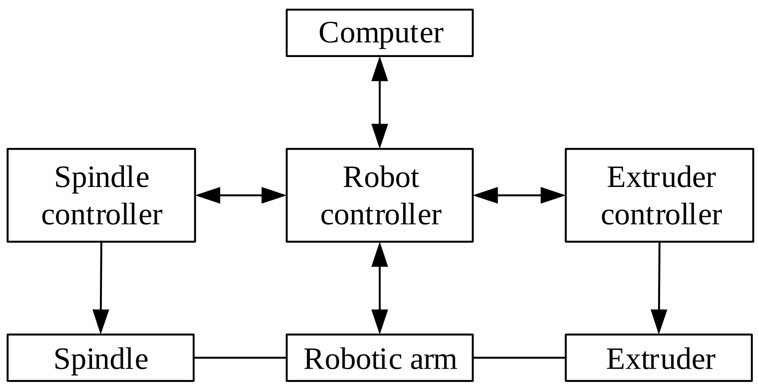


**Fig. 7**. System diagram of the hybrid robotic manufacturing system.

## Impact on Undergraduate Education

Being familiar with various real manufacturing systems is one of the basic requirements for students majoring in manufacturing engineering. However, many engineering courses only talk about manufacturing concepts without hands-on experiments. Hence, students always own the design experience on paper, but are short of real manufacturing experience.

Both subtractive manufacturing approaches and additive manufacturing approaches have advantages and disadvantages in production. The proposed new robotic manufacturing system will integrate both subtractive and additive manufacturing approaches in a way such that the system can produce objects using any or both manufacturing technologies. Students work within a small team with 2~3 students. Students can take full advantage of both subtractive and additive manufacturing technologies. With such a versatile multi-functional robotic manufacturing system, students are able to explore and exercise new and better manufacturing solutions for real-world manufacturing issues. Such an innovative learning experience will train students to be problem-solvers and critical-thinkers in manufacturing. After graduation they will take a leading role in solving real-world manufacturing problems currently facing enterprises and developing future manufacturing solutions that can impact our society.

In their projects, students go through the entire production process with the emphasis on manufacturing. During the processes from three-dimensional (3D) visualization to simulation and form design for manufacturability (DFM), computer-integrated manufacturing (CIM), to product production, assembly, and performance testing, students learn how each process affect manufacturing, think and identify potential design or manufacturing issues, and constantly improve each process to manufacture a better product. Such undergraduate projects on this platform will promote faculty-student connection and inspire students' passion for manufacturing. Moreover, the innovative learning experience provided by the platform embraces the following five principles: *1) The platform emphasizes "learning by doing".* Students gain first-hand experience of the entire manufacturing process by going through each step and learn how it affects manufacturing. *2) The platform fosters critical thinking and logic.* Students think hard and propose and exercise better manufacturing solutions to solve issues observed and to improve the manufacturing process. *3) The platform promotes creativity and innovation in problem solving.* During their research, students are encouraged to creatively explore new and better manufacturing solutions for their specific products. *4) The platform encourages leadership development.* Working within a small team, each student leads the research in his or her expertise (e.g., DFM, CIM, assembly, etc.). Each student will learn and exercise communication, collaboration, and leadership skills. *5) The platform cultivates the attitude of self- and life-long learning.* In their research project, students not only learn by doing, but also develop their own learning styles. With the passion in manufacturing and preferred learning styles, students are cultivated the attitude of self- and life-long learning through this innovative learning experience.

## Conclusion & Future Work

A hybrid robotic manufacturing system was presented in this paper. With both subtractive and additive manufacturing technologies integrated together, it can be used to learn manufacturing knowledge from fundamental to advanced topics, satisfying various levels of students. Such a multi- functional robotic manufacturing system makes it a perfect platform for students not only to creatively learn and apply existing manufacturing technologies, but also to actively explore new and better solutions for manufacturing problems in their team- based undergraduate projects. The platform provides an innovative learning experience that emphasizes learning by doing, fosters critical thinking, promotes creativity and innovation in problem solving, encourages leadership development, and cultivates the attitude of self-learning. With such an innovative learning experience, students will graduate with competency in solving real- world manufacturing problems currently facing enterprises and developing future manufacturing solutions that can impact our society.

In the future, it is possible to integrate other manufacturing approaches into this platform. The recently developed techniques such as machine learning, data visualization, big data and related analysis can enhance manufacturing processes in wide aspects and thus, will also be take into consideration in the future. By utilizing these techniques, the platform can grow more powerful and be used for multiple purposes. Students can experience the most advanced manufacturing technologies and have a broad view towards manufacturing.

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