# Robotic Motion Planning for Cold Spray Additive Manufacturing Challenge Project Concept Document

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## 1 Abstract

Cold Spray is an additive manufacturing technology in which fine metal powders are sprayed at supersonic speeds against a substrate leading to the deposition of metal material. Northeastern University's Cold Spray (CS) Lab's research on the material properties of cold spray technology has been limited by an inability to deposit material in complex patterns and accurately quantify how much material is being deposited.

The CS Lab proposes a project to process a Computer-Aided Design (CAD) model, generate a robotic motion plan, and monitor how much material is being deposited in real time. This project will require the development of software and algorithms to leverage existing robotic and sensing equipment in a safe, accurate, and repeatable manner to make this technology practical for everyday use.

## 2 Background

### 2.1 Cold Spray Technology

Cold spray technology uses pressurized inert gases (helium and nitrogen) heated between 100-600 °C to propel metal particles through specially designed nozzles [1]. Each individual particle ranges from 1 - 150 µm in diameter and is ejected from the nozzle at up to 1200 m/s [2]. Material is built up layer by layer until the desired thickness and geometry is reached. The term "cold" comes from the temperature of the gas relative to the melting point of various types of metals. Keeping the temperature of the gas relatively low prevents the material properties of the metal powders and the substrate from changing, therefore increasing the number of applications cold spray technology can be used in. Cold sprayed parts can also be machined in the same way as traditional metal parts allowing for the parts to be further refined post spraying. Figure 1 details how material is built up using cold spray technology. The

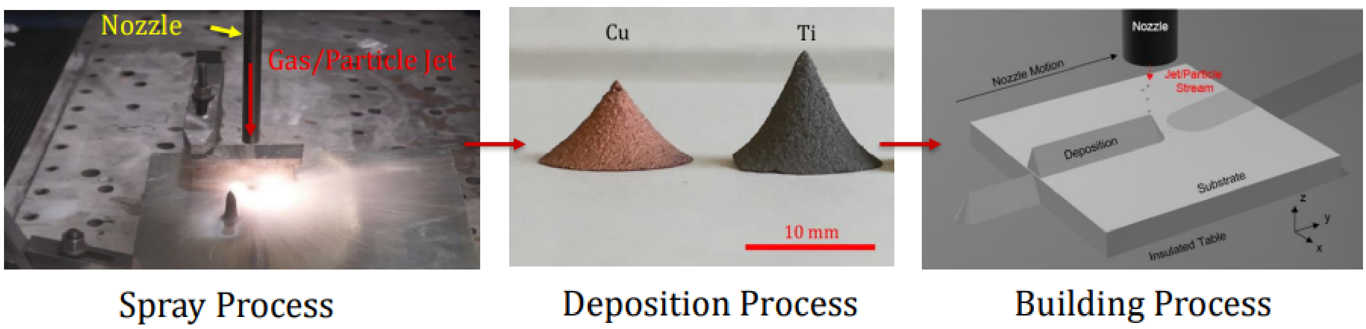


Figure 1: Cold Spray Material Deposition Process [2]

left and right images demonstrate how the nozzle directs the gas/particle jet stream to build up material. The center image of Figure 1 shows that the metal particles are deposited in a circular cone shape. As the particles are sprayed in the same spot, the height and width of the cone increases. This deposition shape adds another level of complexity to accurately deposit material. Complex nozzle motions and angles are needed to build up a flat surface using cone shaped building blocks.

### 2.2 Current Work

Most of the current research being done by the CS Lab is around the materialistic properties of the cold spray technology. Some of this research includes testing how changing various parameters such as powder type, gas type, gas temperature and particle shape impacts the deposition rate and efficiency.

Examining these impacts is limited by the lab's ability to control the robot. Currently only basic trajectories such as a simple back and forth raster paths can be planned for with minimal ability to control the robot's speed along the trajectory. Curved paths are not possible with this method of controlling the robot as functions even as simple as square roots are not possible. The current motion planning techniques are very time intensive and make it difficult to scale up the lab's operations and spray new parts.

The method the lab has employed to estimate the amount of material deposited is to weigh the substrate before and after being sprayed. This method is accurate but is unable to give real-time measurements and only provides data on the total amount of material sprayed.

# 3 Project Requirements

This proposed project is broken up into two phases, in-situ real-time deposition measurement and generating robot trajectories from a 3D CAD model.

## 3.1 In-Situ Real-Time Deposition Measurement

In-situ real-time deposition measurement refers to being able to obtain volume measurements of the amount of material that is being deposited in real time. In addition to the total volume, these measurements need to be broken down into the volume of each layer of material.

Completion of this phase will further other research projects in the lab by being able to quantify how changing the cold spray parameters affects material deposition. Accurately knowing how much material is deposited will also help inform the calculation of robot trajectories later in the project.

Phase one requires the development of software to control the sensor motor, sample profile data from the laser, and analyze that data to calculate the material volume. Phase one is expected to be completed by December 2019.

## 3.2 Robot Trajectory Generation

In order to scale this technology, an efficient and easy way to generate trajectories for the robot is needed. For this phase of the project a CAD model (.step or .stl format) will be loaded into the system. Algorithms need to be developed to process this CAD model and generate a motion plan for the robot. This motion plan will then be executed on existing robot hardware in conjunction with spraying metal powder to produce a physical part.

The result of this phase will be to automatically generate robot trajectories from a CAD model of an open shell structure part. This is intended to be a proof of concept that the CAD processing algorithm works and can be extended further in the future. Phase two is expected to be completed by July 2020.

## 3.3 Leadership

Successful completion of this project will require diverse leadership skills in technical, personal and project management areas.

At the start of this project no robotic software development had taken place so this project will require creating the full software architecture from the ground up. When developing this software architecture the existing hardware and any potential hardware acquisition will have to also be considered.

This project involves people in academia spanning Northeastern's Robotics, Mechanical Engineering, and Electrical and Computer Engineering departments as well as industry professionals at VRC Metals. Strong project management skills will be needed to coordinate between this expansive group. Care will have to be taken to justify critical project decisions to people with and without a working knowledge of robotics and the associated technical jargon.

# 4 Solution

## 4.1 Hardware

The CS Lab has an existing setup on Northeastern University's Burlington campus in partnership with VRC Metal Systems. This lab is equipped with numerous pieces of equipment to support spraying material and analyzing cold sprayed parts. The equipment relevant to this project is outlined below.

### 4.1.1 Fanuc Robotic Arm

The CS Lab's robotic setup includes a Fanuc M-710ic 6 degree-of-freedom robotic arm, the cold spray nozzle, and a rotary positioner table. The Fanuc robot is rated to hold up to 50 kg of material allowing it to easily support the weight of the cold spray nozzle. Attached to the cold spray nozzle are insulated gas and powder feeding lines. The rotary table provides a 7th axis for motion planning and will be able to rotate the part that is being sprayed to enable to robot to spray more complex patterns.

#### 4.1.2 Keyence Laser Profiler and Mount

The CS Lab also owns a Keyence LJ-v7060 sensor. This sensor emits a 16 mm wide laser beam to detect up to 800 individual data points along the surface profile of an object. The Keyence sensor connects to the end effector of the robot via a sensor mount previously developed by a Northeastern University capstone team. This sensor mount contains a motor that rotates the sensor around the nozzle to keep the sensor positioned behind the cold spray nozzle as the robot moves. This motor represents the 8th axis that needs to be controlled by the robot motion planning algorithms. While moving the robot and sensor over the surface of a part, data can be continuously sampled to build up the surface profile.

### 4.2 Software

The primary deliverable will be a full software suite and set of algorithms to control and collect data from the existing robotic hardware. The major software architecture and algorithm decisions are outlined below.

#### 4.2.1 Robot Operating System (ROS)

The Robot Operating System (ROS) will be the basis of the software architecture and robot communication. ROS is a widely used open-source platform for developing, controlling, and simulating a wide variety of robots. ROS has preexisting driver packages for both the Fanuc M-710ic robot and Keyence sensor which will greatly decrease the startup development time.

#### 4.2.2 Trajectory Optimization

There are many different motion planning algorithms that have been developed for controlling robotic arms. Many of these use random based logic to calculate the path between the start and goal points. A random based motion planning algorithm won't work for this application since full control over where the nozzle is pointing is needed to deposit the correct amount of material in the correct spots.

For that reason a trajectory optimization based algorithm (Trajopt) was chosen. Trajopt allows for specifying costs and constraints [3] to have full control over the motion of the cold spray nozzle throughout the entire path from start to end. Trajopt also has an existing ROS package for easy integration with the Fanuc M-710ic robot.

Most of the development time for this project will be spent on fine tuning the trajectory optimization for use in this application. This work will include developing an algorithm to process a CAD model and calculate a path that will enable spraying material to build up the shapes specified by the CAD model. This path will be fed into trajopt to calculate the specific joint positions the robot needs to execute to follow this path. The robot joint states will be optimized for efficiency as well as safety to ensure the human operators and surrounding environment are not in danger of colliding with the robot.

#### 4.2.3 Volume Estimation

The Keyence ROS driver will be used to directly interface with the Keyence sensor and collect surface profile data. Using the Point Cloud Library (PCL) each individual sensor profile measurement will be combined into one large point cloud representing the surface of the deposited material. This point cloud will be processed using the PCL to generate material volume measurements that can be broken down into each layer of material.

To improve the quality of data, the position of the sensor motor will be determined by the trajopt motion planning algorithm. This will allow the Keyence sensor to always be positioned behind the robot nozzle with the laser line perpendicular to the trajectory of the robot. Keeping the laser line perpendicular to the robot motion will ensure full analysis of the part's surface and lead to an improved accuracy of the volume measurements.

An additional benefit of including the sensor motor in the trajopt motion planning is to ensure it will never collide with the robot or environment. The Keyence LJ-v7060 model is valued at approximately $20,000 so it is critical to prevent this piece of equipment from being damaged.

## 5 Market Assessment

As this is a research project in a research lab the immediate goals of this project are not to produce a commercially viable product. The goals of this project are simultaneously to develop tools that support the other research being done in the CS Lab and to determine the feasibility of this technology to be further developed into a commercial product.

### 5.1 Market Value - Part Repair

The United States military has a keen interest in cold spray technology for use in fixing or replacing damaged parts. Many parts used by the military are expensive, are no longer being produced, or would require long lead times to replace [1]. Cold spray technology could be used to repair parts at a fraction of the cost by spraying metal powder over damaged areas without changing the metal properties of the existing part. For parts that are no longer being produced or would take too long to manufacture cold spraying can be used to quickly print an entirely new part in a cost effective manner.

The Navy has saved over $1.6 million on a single part for the F/A-18 fighter jet using cold spray technology. This shows great promise for the future estimated market value of this technology once its use is expanded to other parts. Initial testing has proved very promising as Navy engineers have seen a 20-40% reduction of machine rejected repairs and a 10 times increase in the strength of cold spray repaired parts compared to parts repaired by traditional methods [4].

### 5.2 Market Value - Part Creation

Spee3d is an Australian company working on commercializing 3D printing using a similar process to cold spray. They are using a fixed nozzle to spray aluminum and copper powders with a 6 degree of freedom robot to manipulate the substrate and build complex shapes. Spee3d is primarily targeting the metal casting market by manufacturing parts cheaper and faster. Spee3d has said that the "break-even point is about 10,000 pieces when comparing costs to casting. Our niche is 1 to 10,000 pieces. Properties are the same as cast parts, with the same surface finish. Cast parts are the obvious market..." [5] The metal casting market is projected to be worth $39.94 billion by 2025 [6] while the global additive manufacturing market is projected to be worth above $33.09 billion by 2025 [7] showing considerable promise for cold spray technology to take a share of these markets. Spee3d has shown that their technology can produce limited quantities of a single part at a low cost, something that is not possible with traditional metal casting technologies. Spee3d's technology is currently limited to spraying parts with a final weight under 3 kg with a size less than 300 mm x 300 mm x 300 mm [8] preventing it's usefulness to the military to repair parts.

### 5.3 Value Added to Sponsor

The immediate return on investment in this project for the cold spray lab is added time and data. Initial estimates for this project are that it will take 20-30 minutes to plan robot motions for a new part. This includes the time to load information about the new part, calculate the path, and manually verify the accuracy of the proposed motion plan before executing it. This represents up to a 95% decrease in time required compared to the current methods which can take up to an entire work day. Current planning methods also have no way to visually confirm the robot trajectory is accurate prior to starting the spray.

The completion of this project will provide a research tool to estimate the amount of material deposited in real time. Since there is no current method for quantifying this data the cold spray lab will now be able to take on additional research projects and publish additional research.

## 6 Risk Assessment

### 6.1 Time Resources

The cold spray lab where the robotic equipment is housed is a shared resource between Northeastern and VRC Metals resulting in multiple projects that require use of the cold spray equipment. In order to gain access to this equipment time must be scheduled roughly a week in advance. Limited access to the robotic equipment limits the ability to perform tests verifying the accuracy of the developed algorithms. To mitigate this risk a simulation environment can be setup to run initial tests before running the algorithms on the real robotic hardware. However, this simulation testing is only effective if the simulations are accurate.

### 6.2 Material Resources

The cost of powders, gas and operation time limits the opportunities to test the developed algorithms on the full cold spray system. Accurate material deposition will depend on the development of accurate simulation models which are based on current assumptions about the cold spray technology. A single spray could cost upwards of $2000 depending on the spray conditions and which gas is used.

### 6.3 Hardware Compatibility

Despite there being a Fanuc ROS driver, Fanuc does not officially support ROS so there is no guarantee that the ROS driver will immediately work out of the box with our Fanuc robot. To fix this potential issue more funding may be required to purchase hardware or software upgrades from Fanuc. Additional ROS software development may also be a solution to some of these issues in place of additional funds.

### 6.4 Physical Safety

The cold spray lab has a long list of potential safety concerns ranging from operating industrial-grade robots and lasers to handling metal powders and gases in enclosed spaces. These safety concerns are greatly mitigated by following established lab safety protocols and keeping safety at the forefront of planning and executing every test.

## 7 Conclusion

The proposed project has the ability to revolutionize the additive manufacturing industry by lowering the expected cost and lead times of manufacturing techniques. Delivering this project on time and on budget will require the strong leadership and technical skills outlined above but will also require a passionate team that is committed to making this project a success.

My career goals include obtaining a job that is focused on developing software for robotic motion planning but also includes occasional work with the mechanical implementation of robotic systems as well as developing software in other robotic focus areas. Approximately 50% of the development for this project is focused on creating a motion path for spraying a specific part and translating that proposed path into robotic motions. The remaining 50% deals with software related to robotic perception and integrating and controlling real robotic equipment. My passions uniquely align with this project to further qualify me to lead its technical development.

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