CLEANROOM AUTOMATION OF SRF CAVITY STRING ASSEMBLY

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Abstract

Superconducting radiofrequency (SRF) cavities allow modern accelerators to achieve higher accelerator gradients at orders of magnitude higher efficiency than their copper counterparts, but their highly sensitive and laborious assembly process limits their adoption. Specifically, particulate contamination introduced during cavity string assembly is a primary source of field emissions, and these greatly diminish accelerator performance by generating excessive heat and potentially causing permanent damage to the cavity. In this work we propose a system design for an automated robotic cell for clean assembly of SRF cavity strings with the hope that by automating most of the assembly process, Fermilab can produce enough high-quality SRF cavity strings to meet the demand of current and future projects.

BACKGROUND

Radiofrequency (RF) cavities employ electromagnetic fields to add energy to particle beams. While different experimental questions require distinct cavity performance specifications, several technical factors limit the maximum accelerating gradients achievable with RF cavities. RF cavities have been around for more than a few decades, but recent developments in materials science and engineering have brought forth the age of superconducting radiofrequency (SRF) cavities.

Superconducting Radiofrequency (SRF) Cavities

Niobium cavities have become an enabling technology for particle physics. Superconducting niobium cavities operate with orders of magnitude higher efficiency due to their low surface resistance, and this allows for the construction of accelerators that can reach higher accelerating gradients at a fraction of the power cost.

Table 1: Comparison of parameters for normalconducting and superconducting pillbox cavities

Parameter	Normal Conducting	Super Conducting
Rs(omega)	0.01	$2.0\text{x}10^{-8}$
Q0	25,500	$1.3\text{x}10^{10}$
Pc(W)	198,000	0.04
Ra(omega)	$5\text{x}10^{6}$	$2.5\text{x}10^{12}$

Field Emissions

Field emissions are a phenomenon characterized by RF power loss to electrons that tunnel out of the cavity wall. This phenomenon causes significant power losses, decreasing the cavity's efficiency thereby limiting its max accelerating gradient. Field emissions can also lead to undesirable heat generation which can threaten the cavity's thermal stability. Proven analytical descriptions of the dynamics of field emissions have yet to be developed, but there is a large body of research and consensus agreeing that surface contamination is a primary source of field emissions. This is the main reason high-pressure rinsing and electropolishing are crucial steps in the manufacture of SRF cavities, but a significant challenge to cavity cleanliness is the assembly of cavity strings.

String Assembly

Before cavities can be packaged into cryomodules, cavities need to be assembled into strings. The number and type of cavities in a string depends on the specific application, but the assembly process of most strings needs to happen in the cleanroom. As of today, this process is highly laborious, requires a team of highly skilled cleanroom technicians, and is almost entirely manual. The assembly process consists primarily of joining cavities through interconnecting bellows which are mated at the flanges. The alignment of the flanges, removal and addition of the fasteners, and the vacuum quality control are all mostly done by hand with some help from support fixtures and mechanisms.

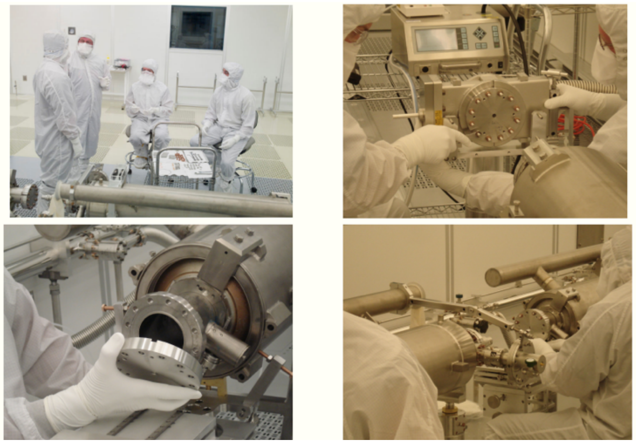
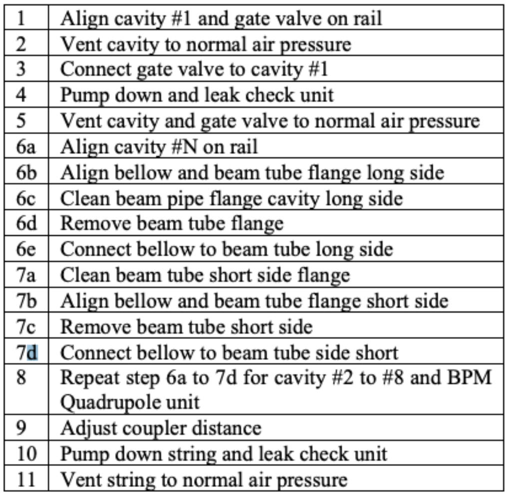


Figure 1: Representative images of cavity string assembly in a class 10/100 cleanroom.

Table 2: Representative list of the workflow for string assembly.



1	Align cavity #1 and gate valve on rail
2	Vent cavity to normal air pressure
3	Connect gate valve to cavity #1
4	Pump down and leak check unit
5	Vent cavity and gate valve to normal air pressure
6a	Align cavity #N on rail
6b	Align bellow and beam tube flange long side
6c	Clean beam pipe flange cavity long side
6d	Remove beam tube flange
6e	Connect bellow to beam tube long side
7a	Clean beam tube short side flange
7b	Align bellow and beam tube flange short side
7c	Remove beam tube short side
7d	Connect bellow to beam tube side short
8	Repeat step 6a to 7d for cavity #2 to #8 and BPM Quadrupole unit
9	Adjust coupler distance
10	Pump down string and leak check unit
11	Vent string to normal air pressure

PROBLEM DEFINITION

Particulate contamination during string assembly is a primary source of field emissions as it is the last step where contact is made with the interior surface of cavities. The focus of the project is to generate concept designs for robotic automation that can reduce human contact with cavities in the cleanroom during string assembly. The first step for generating concepts and ideas is to define technical requirements for system success.

Technical Requirements

A complete string assembly system must address all four of the following requirements:

1. Reliably align flanges of the cavities and interconnecting bellows
2. Clean fasteners, flange holes, and peripheral parts
3. Eliminate human contact with cavity
4. Minimize particulate contamination

Due to the complexity of a complete system and the timeline for this project, the focus of this project is requirement #1. The primary objective for this project is to develop a concept for a robotic system that can reliably align flanges. Recent work in developing automation for cavity assembly has made progress toward solutions or #2 and #3, and from a technical perspective requirement #1 requires the most sophisticated manipulations.

EARLY IDEATION

Given the scope and the timeline for this project, a systematic approach was taken to generate and evaluate many concepts in an efficient manner.

Concept Generation

7 concepts for a robotic cell that could align cavity flanges were generated. The goal of this step was to generate many different concepts in hopes of covering the solution space for this problem. The 7 concepts varied in the number of robotic arms, the type of manipulator employed, and the level of autonomy. Due to the scope and timeline for this project, concepts were only conceived to a high level. Detailed concept designs beyond the sketch level were not generated, and this was done to make more time for concept evaluation. Below are the 7 concepts generated:

Table 3: Summary of the 7 concepts generated

Concept Name	**Description**	**Design configuration**
2-arm system	1 arm for grabbing the cavity and 1 arm for attaching/removing peripheral components	X_1
1-arm system	1 arm with sophisticated tooling to both grab the cavity and attach/remove peripheral components	X_2
6-arm system	1 large arm for cavity manipulation and 5 small ones for attaching/removing peripheral components	X_3
Robotic rail + 5 small arms	robotic rail for cavity manipulation and 5 small arms for attaching/removing peripheral components	X_4
Crane (arm)	human-controlled arm that is exclusively used for manipulation or the cavity. Everything else is done manually by technicians	X_5
Crane + rail	concept 5 with an additional rail	X_6
Modular racks	each cavity fits into a wheeled rack with mechanisms for fine-tuning the cavity's position relative to another rack. Few/no actuators	X_7

Concept Evaluation

To efficiently evaluate the 7 concepts generated, a tradespace-inspired decision matrix was developed.

Tradespace analysis Tradespace analysis is a framework employed by NASA, DARPA, and MIT to critically execute design decisions for projects with complex resource, cost, and architecture structures. The goal of tradespace analysis is to identify compromises and opportunities associated with certain design decisions in a clear and systematic way. While various tools for tradespace analysis exist, this work borrows inspiration from Ross et al. where utility scores are derived for each design configuration and are calculated based on scores for the design across multiple attributes, where an attribute is a metric for measuring how well a design objective is met. Below is the simplified utility score calculation used for this work:

$$U(\boldsymbol{X}) = \sum_{i=1}^{N} k_i u_i(\boldsymbol{X}) \tag{1}$$

Where a design configuration **X** has utility score U(**X**). Attributes each have some function u_i which report on a design configuration's performance on that metric. As an example, number of degrees of freedom was one of the attributes considered for the concepts evaluated here and will be defined as u_1, and will have k_1 of 1. A design configuration **A** consisting of on 6-axis arm on a linear will have a u_1 of 7, and if that is the only attribute, then the utility score U(**A**) of the design configuration will be 7. Below are all the attributes used to evaluate the concepts:

Table 4: Description of the attributes used to evaluate the concepts generated for this project

Attribute	**Description**
u_1	total DOF
u_2	vision system complexity
u_3	end-effector complexity
u_4	potential reduction in labor time
u_5	total contact time between cavity and human
u_6	upkeep

Ultimately, tradespace analysis is most useful when the attributes used are quantifiable, design concepts/configurations can be parametrized and described as matrices, and substantial feedback from stakeholders defines the weights k_i of each attribute. Due to the scope and the timeline for this project, tradespace analysis did not reveal anything not identifiable in a traditional decision matrix, but the potential value in decision-making for larger projects was clear.

Decision matrix A slightly modified decision matrix for the 7 concepts was developed in hopes of highlighting the key advantages and disadvantages of each concept.

Table 5: Decision matrix of all 7 concepts

	u_1	**u_2**	**u_3**	**u_4**	**u_5**	**u_6**	**tot**
X_1	-12	-8	-8	9	9	5	-5
X_2	-6	-9	-10	9	10	3	-3
X_3	-36	-7	-4	9	10	8	-20
X_4	-31	-6	-4	9	10	9	-13
X_5	0	0	-10	5	5	-4	-4
X_6	0	0	-10	7	7	-7	-3
X_7	0	0	0	0	3	0	3

The decision matrix highlighted a bias against classical robotic arm manipulators, and this made sense given that overall complexity is a driver for design feasibility. While none of the concepts generated were selected directly for further development, careful thinking of potential synergies between the highest-scoring concepts led to the idea which became the lead concept for this project: the rail-mounted hexapod. This concept generally consists of a 6-DOF hexapod (also known as a stewart platform) that would sit on a linear rail. The cavity would be placed on the platform, the platform + cavity would be translated down the rail to the first cavity of the string, and the high-resolution movement hexapod would align the two flanges.

MCM DEVELOPMENT

Most-critical modules (MCM) are the primary module which can enable the competition of some design objective. MCMs are generally higher-detailed than concepts or ideas, and they should be defined with solid models at the minimum and with a working prototype in ideal. Due to the scope and timeline for this project, the MCM in this work consists of a high-level CAD model describing the architecture of the robot cell and a RoboDK simulation of the rail-mounted hexapod executing the proposed manipulations.

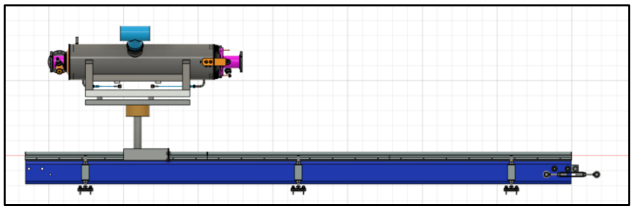


Figure 2: High-level CAD model of the proposed rail-mounted hexapod

The structure underneath the cavity represents the hexapod manipulator but is not to scale. The base represents a carriage mounted on a linear rail which translates the hexapod + cavity up and down the rail.

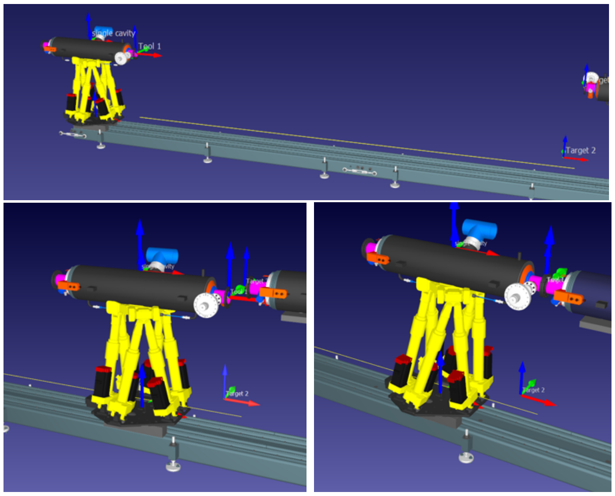


Figure 3: RoboDK simulation depicting flange alignment using a rail-mounted hexapod. (Top) Initial system position after cavity is loaded onto hexapod, (left) second system position when the linear rail brings the cavities close to each other, and (right) is the final system position after the

hexapod adjusts the position of its cavity to fully mate the flanges of the two cavities together.

Figure 4: Zonda S high-precision alignment hexapod.

In addition to a high-level CAD model and a basic RoboDK simulation, a potential hexapod was found and is proposed as a strong option for this application. The Zonda S platform is a 6-DOF hexapod of 140kg vertical payload (cavity weighs around 70kg, for reference) and is ISO graded. Additionally, this hexapod is rated for 0.1 μm resolution, which is sufficient for aligning cavity flanges.

CONCLUSIONS

Automation of SRF cavity string assembly is challenging due to the plethora of technically challenging processes contained within. While a full system design eluded us this summer, in this work we show that flange alignment –the most challenging part of string assembly—can likely be achieved with a rail-mounted hexapod. Hexapods are commonplace in high-precision alignment settings across a wide range of industries, and we believe it could serve well for this application. We hope the early ideation methodology highlighted in this work is useful for future large-scale automation efforts in the lab, and we hope that the CADs and the RoboDK simulations give hope for potential implementations of automation in string assembly.

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