University of Pisa

Italian Summer Students Final Report

Robotic Systems integration for cleanroom SRF assembly at Fermilab

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October 2023

Abstract

Superconducting Radio Frequency (SRF) cryomodule assembly is a critical process that demands the highest levels of contamination control in a cleanroom to ensure product quality and reliability. Within the cleanroom environment, human-driven activities remain the major source of uncontrolled particulate. Moreover, the precise manual alignment of components often exceeds expected timeframes, increasing the risk of particulate migration into the critical inner space of the SRF resonant cavity, and causing extended discomfort for workers. Automation comes as a natural solution to address these challenges.

The goal of this activity is to set up and integrate a robotic system to support cavity coupler installation in the cleanroom environment. Initially, remote control of a 6-axis collaborative robot arm will be implemented as an introductory step towards automation in the cleanroom. Subsequently, the system will be further enhanced by integrating manipulation capabilities through an appropriate end-effector, and computer vision technology to enable accurate pose estimation. This comprehensive approach aims to achieve a fully automated and adaptable assembly process in the partially structured cleanroom environment, thereby enhancing efficiency and mitigating existing challenges for better product quality and workers safety.

Acknowledgement

This activity was launched during the summer of 2023 at SRF Department as part of Italian Summer Students program at the Fermi National Accelerator Laboratory and at other US Laboratories. Since many people helped me during this experience, I wish to leave a few lines to thank them for their support.

My heartfelt gratitude goes to Donato Passarelli, whose combination of friendliness and humor, coupled with unwavering trustworthiness and resolute guidance, made my experience truly enriching and enjoyable.

I extend my sincere appreciation to Genfa Wu for trusting me and always keeping me motivated.

I would like to thank Mattia Parise, for his illuminating insights and sharp ingenuity; Colin Narug, for his commitment to the purpose; Jacopo Bernardini, for his attentive and kind availability; Matteo Giusti, for his consistent, daily, invaluable help.

In the same vein, I owe a debt of gratitude to Giorgio Bellettini, Simone Donati, Emanuela Barzi, Marco Mambelli for granting me this opportunity, and for their exceptional efforts in organizing this high-quality internship program year after year.

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Introduction

Going the long way 'round...

People from Illinois

1.1 Background

1.1.1 International Neutrino Program

Neutrinos, the most abundant and elusive subatomic particles of matter, are fundamental yet mysterious constituents of the universe. While trillions of neutrinos pass through our bodies every second, they remain enigmatic due to fact that only a couple of them will stop and interact during our entire lifetime [1]. Neutrinos hold the key to new physics: understanding their nature and behavior may be essential to unlocking some of the universe's hidden secrets, as an explanation to matter-antimatter asymmetry. This experimental investigation requires powerful new accelerator facilities.

In 2014, US Particle Physics Project Prioritization Panel (P5) endorsed a global particle physics program, launching three comprehensive mega-science projects:

- Proton Improvement Plan-II (PIP-II), the upgrade of the Fermilab accelerator complex to deliver a powerful, multi-megawatt, proton beam.
- Long Baseline Neutrino Facility (LBNF), a dual-site detector facilities platform, comprising the "Near Site" at Fermilab, Illinois, responsible to trasform that proton beam in the world's most intense neutrino beam and housing the near detector, and the "Far Site" at Sanford Underground Research Facility (SURF), South Dakota, accomodating the much larger far detector, with a separation of 1300 km.
- Deep Underground Neutrino Experiment (DUNE), the next-generation neutrino

experiment with precision detectors located at both sites.

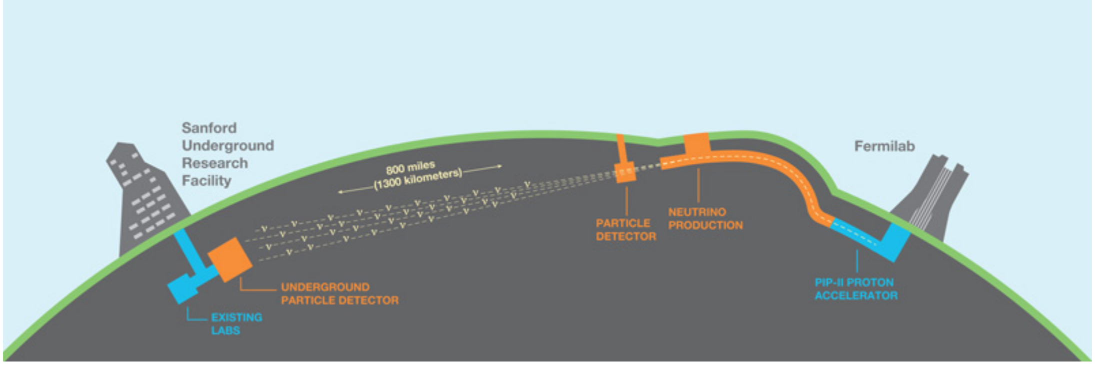

Figure 1.1: Path of neutrinos in the Deep Underground Neutrino Experiment. A proton beam is produced in Fermilab's accelerator complex (improved by the PIP-II project). The beam hits a target, producing a neutrino beam that travels through a particle detector at Fermilab, then through 1300 km of earth, and finally reaches the far detectors at Sanford Underground Research Facility.

The construction of LBNF and DUNE, powered by PIP-II, paves the way for an extensive research program in particle physics that will endure for many decades to come [2].

1.1.2 Proton Improvement Plan-II

The PIP-II linear accelerator (linac) will be the highest-power continuous-wave (CW) proton accelerator ever built; it relies on superconducting radio-frequency (SRF) technology, recognized for its efficiency in particle beam acceleration. The stringent requirements on the accelerating gradient, with quality factor of the PIP-II SRF systems exceeding state-of-the-art, push the boundaries of SRF science and technology, driving broader technological advancements for next-generation accelerators [2].

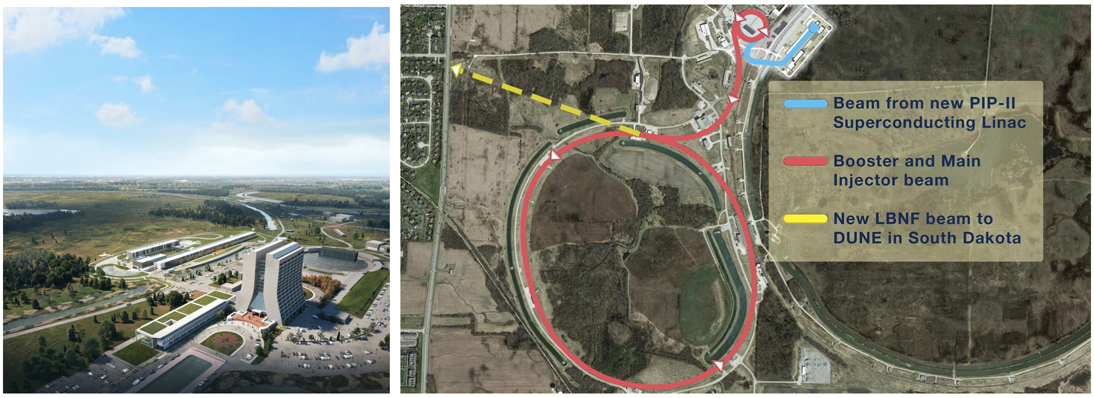

Figure 1.2: The new complex of buildings, located near Fermilab's Wilson Hall, will host PIP-II particle accelerator. It will be the new heart of the Fermilab accelerator complex, that comprises also the existing Booster ring and Main Injector-Recycler.

PIP-II linac will accelerate H-minus ions up to 800 MeV, reaching 84 percent of the speed of light, through 23 cryomodules containing five different types of superconducting cavities: half-wave resonators (HWRs), single-spoke resonators (SSR1 and SSR2), and low- and high-beta 650 MHz elliptical cavities (LB650 and HB650).

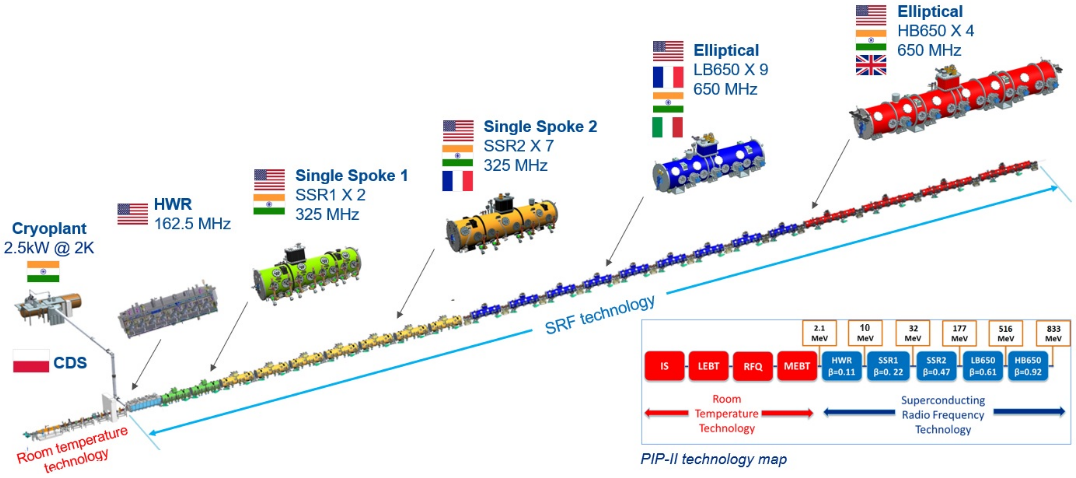

Figure 1.3: The 215 m accelerator is composed of several modules which all work in specific energy ranges.

1.1.3 SRF Technology

Superconducting radio-frequency (SRF) technology is a means of accelerating subatomic or atomic particles like electrons, protons, or ions. In the context of any radio-frequency (RF) accelerator, microwave-frequency electromagnetic fields are generated within a metallic resonant structure, typically referred to as a cavity. Electromagnetic fields are excited in the cavity by coupling in an RF source, an antenna, synchronized within nanosecond precision with the arrival of the bunches of charged particles; so that the particles passing through apertures in the cavity interact with the field and are accelerated forward.

When the RF fed by the antenna matches that of a cavity mode, the resonant fields build to high amplitudes. In the presence of an oscillating field, electric currents flow within the metallic walls of these structures, generating heat that negatively affects the accelerator performance. With superconducting RF, the metallic structure is almost completely lossless. This allows very high field levels, that means a higher accelerating gradient, to be sustained in the resonator without dissipating power that would otherwise melt the structure itself.

Niobium is the current superconducting material of choice. It has excellent superconducting properties at liquid helium temperatures (1.8-4.2 K) [3]. Each cavity has carefully-processed surfaces and is assembled in particulate-free cleanroom.

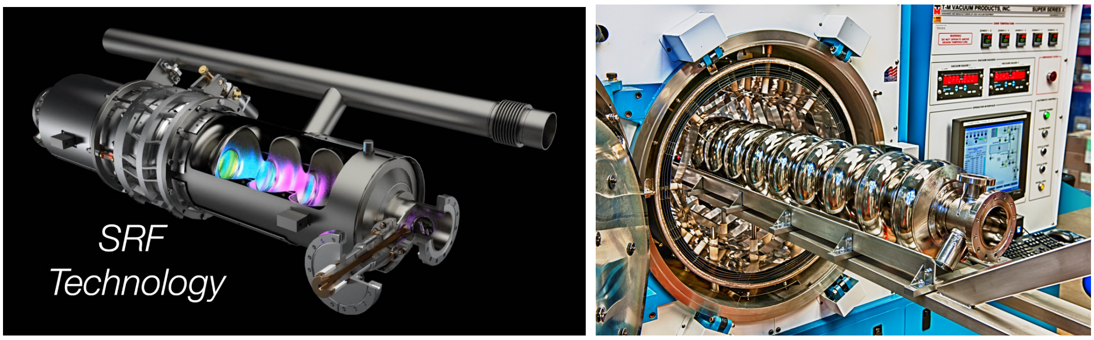

Figure 1.4: A powerful radio-frequency source generates the electric fields that accelerate the particle beam in niobium cavities. To develop and optimize recipes and create new niobium compounds aimed at reducing RF losses is a major focus, and heat treatment for cavities include hydrogen degasification, annealing, and mild baking.

Multiple cavities are collectively assembled into units referred to as cryomodules, which are designed to provide the required insulated cryogenic environment, through the supply of a liquid helium bath. In the case of PIP-II, a total of 23 cryomodules house 116 cavities.

1.1.4 String Assembly

Field emission is a phenomenon that deteriorates the quality factor and limits the accelerating gradient at which a cavity can operate. It involves the emission of electrons from a region with a high electric field and takes place whenever contaminants, such as dust or metal flakes, are present on the inner surface of the cavity.

Scientists mitigate field emission recurring to high-pressure water rinsing, for the purpose of cleaning the interior surface of cavities. This operation must be performed in a cleanroom, which is also used to assemble cavities and pump them down to ultra high vacuum.

Currently, the string assembly process relies on a team of highly skilled technicians, who follow refined procedures in order to minimize particulate generation during cleanroom operations [4, 5]. Nevertheless, human-driven activities remain the major source of uncontrolled particulate. Flange alignment and fastener handling are carried out manually or with the aid of manual tooling and fixtures, lacking consistency and repeatability; the precise manual alignment of components often exceeds expected timeframes, increasing

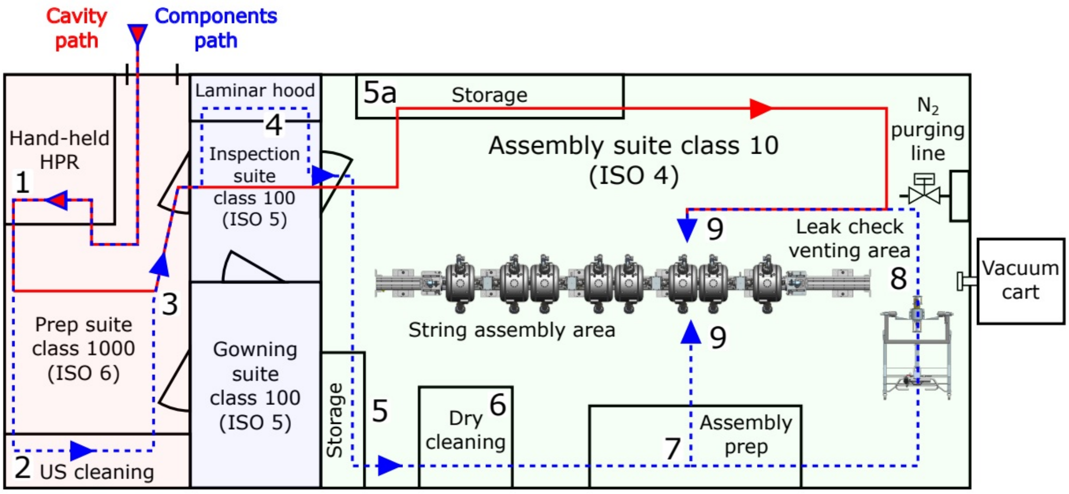

Figure 1.5: Layout of the SRF cleanroom at Lab 2. For a class 10 (ISO 4) cleanroom, particles with a diameter greater than 0.5 µm are limited to 10 per cubic foot.

the risk of particulate migration into the critical inner space of the cavity. This cause also extended discomfort for workers, as contamination control may not always line up with optimal ergonomic solutions.

Figure 1.6: A technician works on the PIP-II 325 MHz spoke resonator cavity string in a cleanroom at Fermilab's Lab 2. Notice the proximity to beamline aperture, necessary to physically access respectively bellow and coupler flange.

1.2 Purpose

1.2.1 Cleanroom Automation

Automation comes as a natural solution to reduce the risk of chemical and particulate contamination during critical assembly steps. The goal of this activity is to set up and integrate a robotic system to support the assembly of SRF components in the cleanroom environment, aiming to enhance efficiency and mitigate existing challenges for better product quality, performances repeatability and workers safety.

1.2.2 Development Strategy

To define the problem, two distinct sources of risk for particulate contamination are identified:

(A) The proximity of humans to beamline aperture, representing a significant source of uncontrolled particulate.

(B) The lack of precision in manual alignment, which results in particulate production through contact between metal surfaces and an extended timeframe for particles migration.

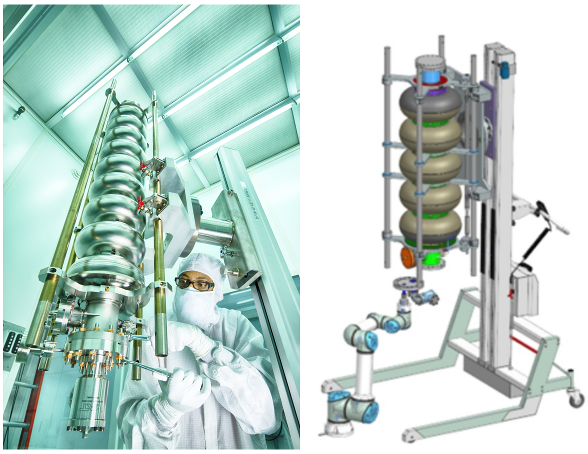

Figure 1.7: A technician and a robot performing a vertical test final assembly.

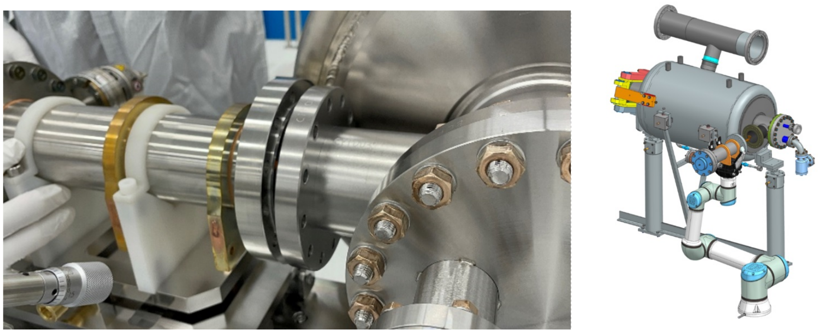

Figure 1.8: Manual and robotic flange alignment for a power coupler insertion

Incremental development of automation capabilities is planned, with the goal of gradually tackle both problems, evaluate effectiveness of solutions through intermediate demonstrations, and likely encounter "lessons to be learned":

(I) Remote Control: a collaborative robot arm can be used by technicians as a tool for acting at distance. This serves as a mitigation strategy for (A) and is achievable in the short-term.

(II) Autonomous alignment: the fully automated and adaptable assembly process within the partially structured cleanroom environment relies on both force sensing and visual perception. This adresses also (B) for the long-run.

Robot-Assisted Assembly

2.1 Configuration

A collaborative robot arm was purchased. The UR16e is a 6-DOF cleanroom compatible robotic arm designed and manufactured by Universal Robots [6]. With a maximum payload of 16 kg when vertically mounted, it can handle a power coupler installed on its distal flange through a specialized tooling fixture. It can reach poses in a radius of 900 mm with repeatability of 50 µm.

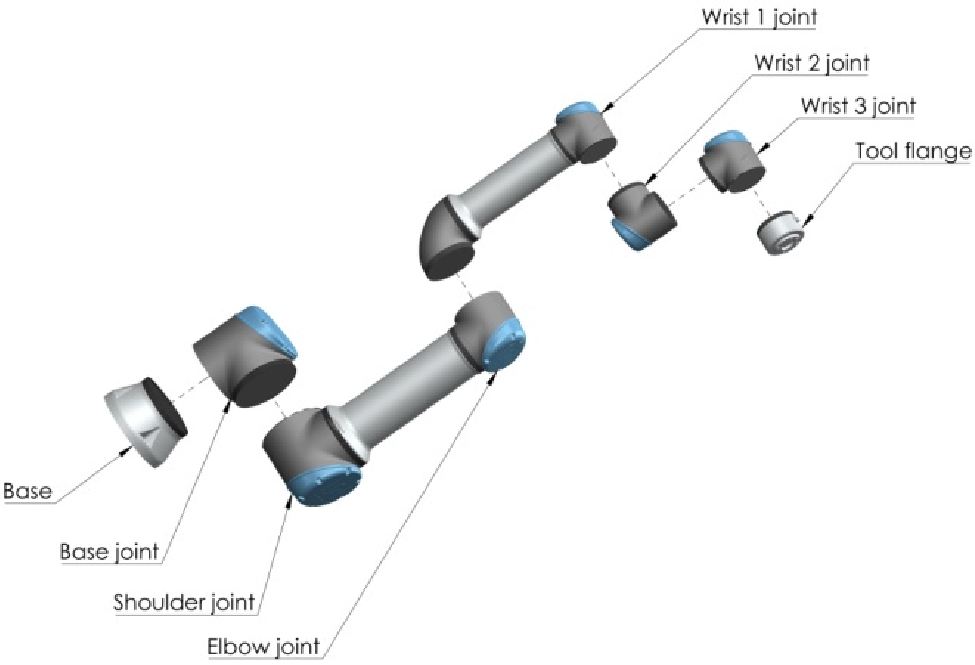

Figure 2.9: Links and joints of UR16e robot arm

The robot features a user-friendly, plug-and-play programming interface called PolyScope, accessible through a Teach Pendant that operates the robot arm via a touchscreen. This is connected to a Control Box, which houses the physical electrical Input/Output interfaces.

The base flange of the robot arm has been mounted on a mobile cart table, enabling the reconfiguration of its relative position with respect to the cavity support fix rail. It is important to choose a predefined configuration that ensures the final pose is achieved without encountering singularities and without obstructing the vertical airflow in the critical zone of the aperture.

An assembly area was reconstructed in the Industrial Center Building (ICB), where preliminary tests were conducted using 3D-printed plastic replicas of a coupler and a cavity. However, the applicability of the successful results achieved in this simulated setting to real-world scenarios is limited: heavy payload and tight tolerances are crucial factors significantly impacting performance, and they were not accurately mimicked by the plastic artifacts used in the test. Moreover, it is desirable to establish the final installation configuration, including measured payloads and auxiliary frames. Transitioning to actual component testing provided for a more accurate representation of real geometric and physical parameters at stake.

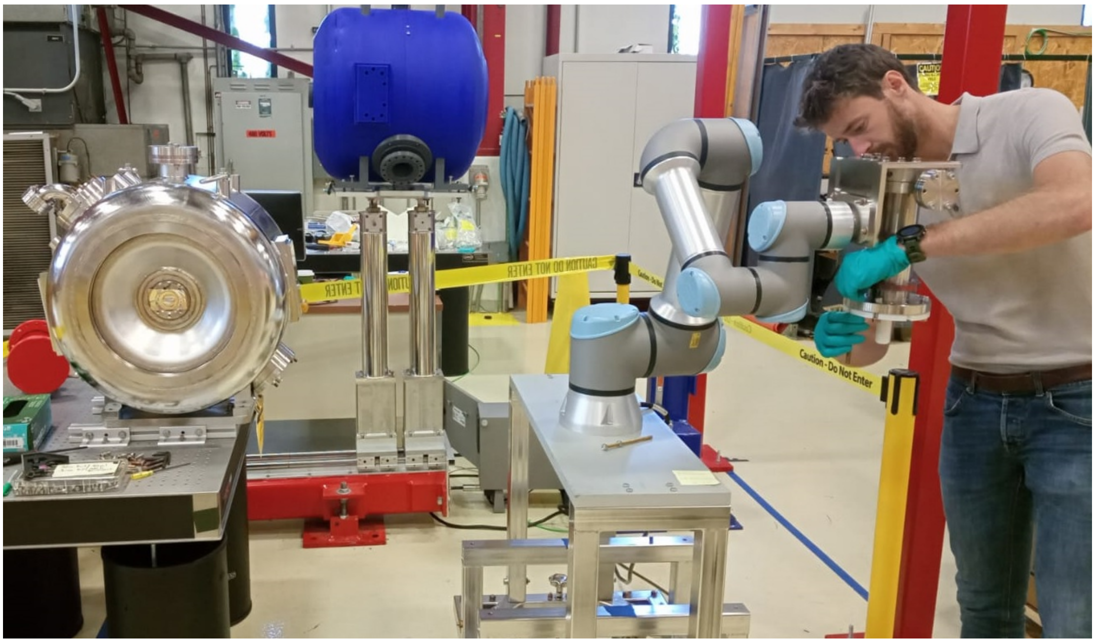

Figure 2.10: Assembly test with real coupler and cavity components

A risk analysis was conducted before the robot arm was powered on for the first time. Proper safety configuration settings, as well as the need for an additional emergency stop button, were determined. Detailed information on risk assessment and safety training is provided in separate documentation [7, 8, 9].

2.2 Procedure

A procedure for the first robot-assisted installation of an SSR2 coupler in the cleanroom has been outlined in a dedicated technical document [10]. The document is divided into four sections, each detailing the steps required for the insertion:

- **Material checklist**: each component has a corresponding ID tag and must be diligently tracked.
- **Cleanroom preparation**: components require thorough inspection and meticulous cleaning, following specialized protocols tailored to each class.
- **Installation Setup**: the cart table must be positioned relative to the lollipop stands and fixed to the rail, and then a safe protocol for the robotic system bring-up must be followed.
- **Installation Process**: the program routine must be enabled and supervised while running through following steps:
    1. Move to predefined tooling installation position.
    2. Engage brakes; perform installation and change payload accordingly; release brakes.
    3. Move in the predefined approach position.
    4. Perform alignment using remote control (I) or computer vision (II); save target position.
    5. Move to predefined cleaning position.
    6. Clean (blow dry with filtered N_2 while monitoring a particle counter).
    7. Move back to target position.
    8. Push flanges against each other using cartesian force-position control (I) or vision based impedance control (II).
    9. Use fasteners for sealing; change payload according to tool load cell data and uninstall coupler from arm tool.
    10. Move to home position

Autonomous System

3.1 Setup

3.1.1 Operating System

Linux Ubuntu 22.04 Jammy Jellyfish has been installed alongside an existing Windows installation in a dual-boot configuration on one of the lab property laptops. The specific tutorial guide is available [11].

High control frequency might lead to non-smooth trajectory execution if not run using a real-time-enabled system. In order to use robot drivers, real-time support was added, compiling the sources of 6.1.46-rt13 real-time kernel and setup user privileges to execute real-time tasks.

CPU speed scaling was disabled, as visual servoing performaces are sensitive to clock frequency changes [12].

3.1.2 Middleware

The Robot Operating System (ROS) is a set of software libraries and tools for building robot applications. From drivers to state-of-the-art algorithm. It was selected for this project due to its modularity, middleware support, community-driven ecosystem, real-time capabilities, and extensibility, all of which make it a robust and versatile framework for developing complex robotic systems.

The stable distribution ROS 2 Iron Irwini was installed from Debian packages available for Ubuntu 22.04 Jammy Jellyfish. One can follow related documentation [13].

Universal Robots ROS 2 driver was installed on top of that from binary packages [12].

3.1.3 Containerization

Containerization is a lightweight form of virtualization that packages applications and their dependencies into isolated units called containers. Containerizing a full system simulator offers the advantage of creating an isolated environment with reproduced interfaces, ensuring the developed solutions are consistent and easily portable to the real-world system.

Docker desktop containerization platform was installed from Debian packages, following the official guide [14].

3.1.4 Networking

The robot was connected to the remote PC using a direct Ethernet connection with static IP addresses. This choice was made to ensure reliability and minimize latency introduced by network hardware.

A concise set of Linux shell commands that enable communication over the network was collected in a cheat sheet document [15].

3.1.5 Calibration

Each robot is calibrated inside the factory to determine exact forward and inverse kinematics, thereby compensating for inaccuracies resulting from manufacturing tolerances. It is highly recommended to utilize this calibration, as neglecting it can lead to position errors reaching magnitudes on the order of centimeters [12].

Calibration data was extracted directly from the robot and stored into a package dedicated to that purpose. Overlaying the custom workspace `srf_robotics` it is possible use launch files for the robotic system [15].

3.1.6 User Interface

To control the arm from the external computer, the External Control URCap program was installed and configured from Teach Pendant[12].

After bringing up the system from both ends, the user and additional nodes running perception and control programs can access the interface for communication with the robot driver. Specifically, in the joint-space the actual state of the robot can be read subscribing to the `/Joint_states` topic and the reference state can be commanded sending a goal to the `/follow_joint_trajectory` action [15].

3.1.7 Monitoring and Logging

PlotJuggler is a fully ROS2 compatible drag-and-drop interface to visualize in a simple way off-line and real-time data, and logs [16].

For instance, force and torque data measured by the integrated tool load-cell can be streamed subscribing to `/wrench` topic and then plotted in a scope window [15].

3.1.8 Simulator

URSim is the offline simulator by Universal Robots. Packed into a container connected over a docker bridge network it acts almost identically to a real robot connected over the real network [12].

To simulate the full system, another container connected on the same docker bridge network emulates the remote computer itself. This is just a virgin container with a minimal version of ROS 2 running on Ubuntu.

Additionally, there are ancillary containers that serve as ports and display forwarders for Virtual Network Computing (VNC) connection to both primary containers. This allows for screen sharing and interaction from a standard web browser. [15].

3.2 Future tasks

3.2.1 Computer Vision System

The next significant step in the project involves the development and integration of a Computer Vision subsystem. This decision is primarily driven by the proven cost-effectiveness and versatility of computer vision solutions, which have consistently demonstrated potential in various applications.

The roadmap includes hardware procurement, the development of a calibration setup and procedures to measure intrinsic and extrinsic parameters within stringent precision requirements, and the implementation of effective algorithms for feature-based extraction and model-based pose estimation.

3.2.2 Safe and Reliable Motion Control

Compliance of the end effector during fastening phase is an crucial prerequisite for a stable and reliable interaction among sealing surfaces. Moreover, direct control in task space is mandatory for visual servoing, whereas integrating a full planning stack as MoveIt is unnecessary for local final motion.

The excellent work of Scherzinger et al. [17] led to release of Cartesian Controllers by FZI Forschungszentrum Informatik [18]. This package offers a ready implemented suite of controllers that are designed to fulfill these requests. Integration of Cartesian Controllers package is a fast and favourable possibility for the project. Its utilities are also compatible with the usage of an user-friendly joystick, which comes highly recommended based on feedback from cleanroom technicians.

Conclusions

Not all donuts come with a hole

People from Illinois

Automation of SRF assembly in cleanroom environment offers a promising and systematic approach to improve the efficiency and consistency of the process.

The work conducted in this activity marks the initial steps of a broader journey, and has established the groundwork for the gradual development of the robotic system capabilities. The availability of a full containerized simulator and the use of Robot Operating System modular framework play a central role in streamlining future advancements. Establishing interfaces with robot driver is beneficial for saving time and resources during the integration of perception packages.

Progressive stages of robot deployment through remote control, intermediate demonstrations, and operator training are pivotal for drawing attention to practical challenges and details, evaluating progress effectively.

The next immediate goal is to perform the first robot-assisted insertion of a power coupler on a cavity in the actual cleanroom. Future steps might include the integration of computer vision for accurate alignment and compliance control for smooth interaction during critical sealing phase.

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