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They were leaders in building the early foundation of modern programming and unveiled the structure of DNA Their work inspired environmental movements and led to the discovery of new genes They've gone to space and back taught us about the natural world dug up the earth and discovered the origins of our species They broke the sound barrier and gender barriers along the way The world of research wouldn't be the same without the pioneering efforts of famous research works made by these women Be inspired by these explorers and early adopters- the women in research who helped to shape our society We invite you to sit with their stories and enter new areas of understanding This list is by no means a complete record of women to whom we are indebted for their research work but here are of history's greatest research contributions made by...

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Research papers and articles

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Development of a Structural Model for Constructing a Cutting Tool Trajectory Analysis Module in the Axiom Control CNC System

Gusev Sergey Sergeevich

ABSTRACT

Justification. Currently, metalworking machines are used in various industries. The operation of these machines, designed for numerical control (CNC), is impossible without the use of appropriate systems that allow for the operational configuration of the system to solve various technological problems by controlling the machine's drives.

The purpose of this work is to comprehensively analyze the functionality of the Axiom Control CNC visualization module in order to identify its strengths and weaknesses compared to similar systems on the market. In the course of the research, a detailed review of existing technologies and visualization methods used in numerical control systems will be conducted, which will allow for a deeper understanding of current trends and needs in this area. Materials and methods. To achieve this goal, the following task has been set, aimed at expanding the functionality of the cutting tool rendering module in the Axiom Control CNC system, namely, the analysis of existing visualization tools for the trajectory of cutting tools in CNC systems.

Keywords: manufacturing, industry, metalworking, technological tasks, visualization of the axiom control CNC system.

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Development of a Structural Model for Constructing a Cutting Tool Trajectory Analysis Module in the Axiom Control CNC System

Разработка Структурной Модели Построения Модуля Анализа Траектории Режущего Инструмента В Системе Чпу «аксиома Контрол»

Gusev Sergey Sergeevich

ABSTRACT

Justification. Currently, metalworking machines are used in various industries. The operation of these machines, designed for numerical control (CNC), is impossible without the use of appropriate systems that allow for the operational configuration of the system to solve various technological problems by controlling the machine's drives.

The purpose of this work is to comprehensively analyze the functionality of the Axiom Control CNC visualization module in order to identify its strengths and weaknesses compared to similar systems on the market. In the course of the research, a detailed review of existing technologies and visualization methods used in numerical control systems will be conducted, which will allow for a deeper understanding of current trends and needs in this area. Materials and methods. To achieve this goal, the following task has been set, aimed at expanding the functionality of the cutting tool rendering module in the Axiom Control CNC system, namely, the analysis of existing visualization tools for the trajectory of cutting tools in CNC systems.

АННОТАЦИЯ

Обоснование. В настоящее время в различных отраслях промышленности используются станки для металлообработки. Работа этих станков, рассчитанных на числовое программное управление (ЧПУ) невозможна без использования соответствующих систем, которые позволяют осуществлять оперативное конфигурирование системы для решения различных технологических задач путем управления приводами станка.

Цель данной работы заключается в комплексном анализе функциональных возможностей модуля визуализации системы ЧПУ «АксиОМА Контрол» с целью выявления его сильных и слабых сторон по сравнению с аналогичными системами на рынке. В процессе исследования будет проведен детальный обзор существующих технологий и методов визуализации, используемых в системах числового программного управления, что позволит глубже понять текущие тенденции и потребности в данной области.

Материалы и методы. Для достижения цели поставлена следующая задача, направленная на расширение функциональных возможностей модуля отрисовки режущего инструмента в системе ЧПУ «АксиОМА Контрол», а именно, анализ существующих средств визуализации траектории режущего инструмента в системах ЧПУ.

Keywords: manufacturing, industry, metalworking, technological tasks, visualization of the axiom control CNC system.

Ключевые слова: производство, промышленность, металлообработка, технологические

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технологические задачи, визуализации системы ЧПУ «АксиОМА Контрол».

Author: PJSC «Rostelecom», candidate for a degree, Energy Engineer.

Сведения об авторах: ПАО «Ростелеком», соискатель, инженер-энергетик отдела энергетиков,

I. ВВЕДЕНИЕ

В современном промышленном производстве станки для металлообработки занимают центральное место в процессе создания высококачественной продукции. Особенно выделяются станки с ЧПУ, которые характеризуются высокой точностью, эффективностью и надежностью. Эти преимущества делают их незаменимыми в таких критически важных отраслях, как аэрокосмическая промышленность, производство медицинских приборов, автомобилестроение, а также в военной и оборонной технике.

Эффективная эксплуатация станков с ЧПУ невозможна без интеграции сложных систем управления, которые обеспечивают оперативное конфигурирование для выполнения разнообразных технологических задач. Эти системы управления играют ключевую роль в процессе автоматизации, позволяя точно контролировать работу приводов станка и обеспечивая высокую степень согласованности между различными компонентами производственного процесса.

В существующей литературе представлено множество подходов к управлению металлорежущими станками, что свидетельствует о разнообразии методов и технологий, используемых в данной области. В частности, описаны принципы построения и функциональные возможности систем ЧПУ, включая их конструктивные особенности и алгоритмы управления. Эти исследования подчеркивают важность разработки и внедрения инновационных решений, направленных на оптимизацию процессов управления и повышения общей производительности.

Кроме того, современные системы ЧПУ все чаще интегрируются с передовыми технологиями, такими как искусственный интеллект и машинное обучение, что открывает новые горизонты для повышения эффективности и качества обработки материалов. Эти инновации позволяют не только улучшить точность обработки, но и снизить затраты на производство, что является важным фактором в условиях жесткой конкуренции на рынке.

Таким образом, дальнейшее развитие технологий управления станками с ЧПУ и их интеграция с современными информационными системами представляют собой важные направления для повышения конкурентоспособности и эффективности производственных процессов в различных отраслях [1].

В данной работе мы сосредоточимся на функциональных возможностях модуля визуализации системы ЧПУ «АксиОМА Контрол», проводя сравнительный анализ с другими известными системами аналогичного типа. Основная цель исследования заключается в расширении функциональных возможностей модуля, отвечающего за отрисовку траектории режущего инструмента в системе ЧПУ «АксиОМА Контрол». В частности, мы будем анализировать существующие средства визуализации траектории режущего инструмента, используемые в различных системах ЧПУ, чтобы выявить их сильные и слабые стороны.

Научная новизна данной работы заключается в разработке методики анализа траектории режущего инструмента, которая отличается уникальной реализацией алгоритмов и представлением данных. Это позволит не только повысить точность визуализации, но и улучшить взаимодействие пользователя с системой, сделав процесс управления более интуитивным и эффективным. Мы уверены, что предложенные усовершенствования откроют новые горизонты для применения системы «АксиОМА Контрол» в различных отраслях, способствуя повышению качества и эффективности производственных процессов.

II. ПОСТАНОВКА ЗАДАЧИ

Цель данной работы заключается в комплексном анализе функциональных возможностей модуля визуализации системы ЧПУ «АксиОМА Контрол» с целью выявления его сильных и слабых сторон по сравнению с аналогичными системами на рынке. В процессе исследования будет проведен детальный обзор существующих технологий и методов визуализации, используемых в системах числового программного управления, что позволит глубже понять текущие тенденции и потребности в данной области.

Кроме того, особое внимание будет уделено разработке модуля анализа траектории перемещения режущего инструмента, который станет неотъемлемой частью модуля визуализации. Этот новый функционал направлен на автоматизацию процесса анализа и улучшение точности визуализации, что в свою очередь позволит операторам более эффективно контролировать и оптимизировать производственные процессы.

В результате выполнения работы планируется не только расширить функциональные возможности модуля визуализации, но и предложить рекомендации по его дальнейшему развитию, что обеспечит более высокую степень интеграции с другими компонентами системы ЧПУ и повысит общую производительность и качество обработки материалов. Таким образом, данная работа будет способствовать созданию более совершенной и конкурентоспособной системы ЧПУ «АксиОМА Контрол».

III. РАЗРАБОТКА ДИАГРАММЫ ПРЕЦЕДЕНТОВ МОДУЛЯ АНАЛИЗА

Непосредственно перед началом разработки построена диаграмма прецедентов модуля анализа, главная задача, которой, состоит в описании функциональности разрабатываемого компонента и структурной схемы, предназначение которой состоит в наглядном представлении взаимодействия частей модуля анализа в основных режимах работы.

Для разработки модуля анализа траектории режущего инструмента, в первую очередь необходимо определить основные функциональные требования разрабатываемого приложения [2]. На рис. 1 представлена полная диаграмма прецедентов. Проведения пользователем анализа, в принципе невозможно без поступления каких-либо входных данных, следовательно, самый первый прецедент должен отражать обеспечение данной функциональности. Вследствие этого, сформирован прецедент «Обработка входных данных», который включает в себя:

- прием файла с реальными координатами;
- прием файла с рассчитанными координатами;
- осуществление предварительной проверки данных на корректность их ввода.

После поступления входных данных, чтобы провести их анализ, необходимо осуществить над ними некоторые манипуляции, для этого необходимо внедрить алгоритмы работы, по которым выполняется анализ. Все это содержит прецедент «Выполнение расчетов», в который входят:

- расчет отклонений между реальными и рассчитанными координатами;
- вычисление среднеквадратического отклонения;
- выполнение алгоритма k-средних за счет машинного обучения.

Для полноценной работы с модулем анализа у пользователя должна быть возможность сохранить полученные результаты (прецедент «Сохранение результатов»), а именно:

- рассчитанных модулем отклонений, для удобства в форматах TXT или EXCEL;
- графика построенного по отклонениям
- графика с результатами работы алгоритма k-средних.

Разумеется, так как разрабатываемый модуль анализа является веб-приложением, он должен иметь масштабируемый интерфейс для взаимодействия с элементами (прецедент «конфигурация интерфейса»).

Рис. 1: Диаграмма прецедентов модуля анализа

IV. РАЗРАБОТКА СТРУКТУРНОЙ СХЕМЫ ПОСТРОЕНИЯ МОДУЛЯ АНАЛИЗА ТРАЕКТОРИИ РЕЖУЩЕГО ИНСТРУМЕНТА

Структурная схема модуля анализа траектории режущего инструмента, приведенная на рис. 2, отражает общее взаимодействие компонентов и разрабатываемого модуля, отвечающего за выполнение анализа траектории режущего инструмента.

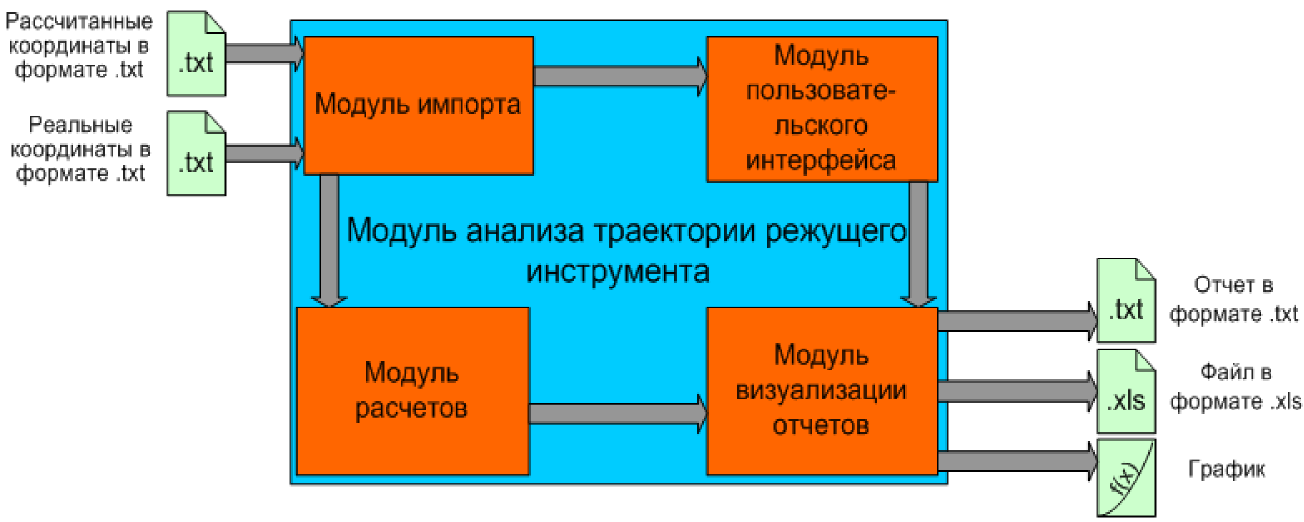

Рис. 2: Структурная схема модуля анализа траектории режущего инструмента

В представленной структурной схеме модуля анализа траектории режущего инструмента, продемонстрирована общая связь между модулями. Работа представленного модуля анализа начинается с загрузки входных данных.

Входные данные представляют собой два текстовых документа выгруженных из системы ЧПУ «АксиОМА Контрол», которые содержат значения реальных и рассчитанных координат. Далее файлы загружаются в модуль импорта, который в свою очередь осуществляет предварительную проверку данных на наличие ошибок. Производится проверка файлов на различные ошибки, разное количество строк координат, отсутствие оси, некорректно загруженный формат документов. При этом, за графическое представление всех элементов в веб-приложении отвечает модуль пользовательского интерфейса [3].

После загрузки и проверки координат данные обрабатываются модулем расчетов, задача которого проводить анализ данных через работу встроенных разработчиком алгоритмов. Также в модуль расчетов входят любые расчеты, связанные со счетом, например, расчет отклонения между реальными и рассчитанными координатами. Анализ по алгоритмам, которые будут введены в модуль расчетов, можно будет графически увидеть в модуле пользовательского интерфейса.

Пользовательский интерфейс будет демонстрировать любое действие графически, загрузку входных данных, а именно реальных и рассчитанных координат, рассчитанные отклонения, также графически отображать алгоритмы, графики и все кнопки действий. Режущий инструмент (РИ) связан с модулем визуализации отчетов.

После проведения анализа за представление и сохранение результатов работы отвечает модуль визуализации отчетов. Данный модуль должен выводить сохранение различных посчитанных отклонений в файлы различного типа. Также предоставлять возможность производить сохранение графика в отдельный файл, для проведения дальнейшего анализа траектории. На выводе из модуля визуализации отчетов, можно вывести три файла, а именно: отчет в формате *.txt, файл в виде *.xls, а также выводить график в формате изображения.

V. РАЗРАБОТКА АЛГОРИТМОВ АНАЛИЗА ТРАЕКТОРИИ РЕЖУЩЕГО ИНСТРУМЕНТА

5.1 Проведение анализа траектории режущего инструмента с помощью «среднеквадратичного отклонения»

Среднеквадратическое отклонение – в теории вероятности и статистики, самый распространенный показатель рассеивания значений случайной величины относительно ее математического ожидания. Указанные термины обозначают корень квадратный из дисперсии случайной величины, и иногда могут означать вариант оценки этого значения. Обозначается σ (сигма) или S [4].

Среднеквадратическое отклонение представляет собой важный статистический показатель, который измеряется в тех же единицах, что и сама случайная величина. Этот параметр играет ключевую роль в различных областях статистики и применяется в ряде аналитических задач. Среднеквадратическое отклонение используется, например, для расчета стандартной ошибки среднего арифметического, что позволяет оценить надежность полученного среднего значения выборки.

Кроме того, среднеквадратическое отклонение является неотъемлемым элементом при построении доверительных интервалов, которые дают возможность оценить диапазон, в котором с заданной вероятностью находится истинное значение параметра генеральной совокупности. В контексте статистической проверки гипотез среднеквадратическое отклонение также служит критерием для определения значимости результатов, позволяя исследователям делать выводы о наличии или отсутствии статистически значимых различий между группами.

Среднеквадратическое отклонение оценивает степень разброса значений в наборе данных относительно среднего значения. Чем больше значение среднеквадратического отклонения, тем больше рассеяние данных: это указывает на то, что значения сильно отличаются от среднего. В то время как малое значение среднеквадратического отклонения говорит о том, что данные сконцентрированы близко к среднему значению.

Таким образом, среднеквадратическое отклонение является важным инструментом для анализа данных, позволяя исследователям и аналитикам глубже понять структуру и характеристики исследуемых величин. Его применение охватывает широкий спектр дисциплин, от экономики до биостатистики, и обеспечивает более точное и информированное принятие решений на основе статистических данных.

Если x_i это i-й элемент выборки, n-объем выборки, а $\bar{x}$ — это среднеарифметическое выборки:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n}(x_1 + \ldots + x_n)$$

То стандартное отклонение на основании смещённой оценки дисперсии (иногда называемой просто выборочной дисперсией), будет записываться следующим образом:

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}.$$

Если говорить в прямом смысле, то это среднеквадратическое разностей измеренных значений и среднего значения.

Среднеквадратическое отклонение является важным статистическим показателем, который предоставляет ценную информацию о распределении данных в наборе измерений. Оно позволяет оценить, насколько сильно отдельные значения отклоняются от среднего арифметического, тем самым демонстрируя степень вариативности в данных.

Среднеквадратическое отклонение является одним из наиболее распространенных и информативных статистических показателей, используемых для анализа разброса данных в различных областях науки и практики. Оно предоставляет ценную информацию о вариативности набора данных, позволяя исследователям оценить степень отклонения отдельных значений от среднего. Важно отметить, что среднеквадратическое отклонение не только служит инструментом для вычисления разброса, но и помогает выявлять аномальные значения, которые существенно отличаются от среднестатистических.

Аномальные значения, или выбросы, могут проявляться как чрезмерно высокие, так и низкие отклонения, что может указывать на различные проблемы в процессе сбора данных. Например, в медицинских исследованиях, где анализируются показатели здоровья, такие как уровень холестерина или артериальное давление, отклонения от нормальных значений могут сигнализировать о наличии патологии или изменениях в состоянии здоровья пациентов. Эти аномалии требуют особого внимания, поскольку они могут указывать на ошибки в измерениях, наличие систематических сбоев в оборудовании или влияние внешних факторов, таких как стресс или диета, на результаты.

Кроме того, использование среднеквадратического отклонения в сочетании с другими статистическими методами, такими как анализ вариации, корреляционный и регрессионный анализ, может значительно повысить точность и надежность выводов. Например, в контексте клинических испытаний применение среднеквадратического отклонения позволяет исследователям более точно оценивать эффективность новых лекарств, выявляя как общие тенденции, так и индивидуальные реакции пациентов на лечение.

Также стоит отметить, что в современных исследованиях, особенно в области больших данных и машинного обучения, среднеквадратическое отклонение служит основой для более сложных методов анализа, таких как метод главных компонент и алгоритмы кластеризации. Эти методы позволяют не только анализировать данные, но и визуализировать их, что значительно упрощает процесс интерпретации результатов и принятия решений [5].

Таким образом, среднеквадратическое отклонение является не просто статистическим инструментом для оценки разброса данных, но и важным элементом в процессе принятия обоснованных решений. Оно помогает исследователям и аналитикам выявлять закономерности, определять нормальные и аномальные значения, а также проводить более глубокий анализ данных. В условиях, когда высокая степень доверия к результатам исследований имеет критическое значение, использование среднеквадратического отклонения в сочетании с другими статистическими методами становится особенно актуальным, способствуя более точному и надежному пониманию исследуемых явлений и процессов.

5.2 Применение метода «k-средних» для анализа траектории режущего инструмента

Метод k-средних (k-means) представляет собой один из наиболее популярных алгоритмов кластерного анализа, который нацелен на разделение m наблюдений на k кластеров (рис. 3). Основная задача этого метода заключается в том, чтобы каждое наблюдение было отнесено к тому кластеру, центроид которого находится ближе всего к данному наблюдению. Это позволяет эффективно группировать данные, основываясь на их схожести.

Принцип работы алгоритма k-средних заключается в минимизации суммарного квадратичного отклонения точек данных от центров кластеров, что выражается через функцию потерь. Алгоритм последовательно обновляет положение центроидов, чтобы достичь наилучшего возможного разделения данных. В начале процесса выбирается k случайных центроидов, после чего каждое наблюдение классифицируется в соответствии с ближайшим центроидом. Затем центроиды обновляются, вычисляя среднее значение всех точек, относящихся к каждому кластеру. Этот процесс повторяется до тех пор, пока изменения в центрах кластеров не станут незначительными или не достигнут заранее заданного числа итераций [6].

Метод k-средних имеет ряд преимуществ, таких как простота реализации и высокая скорость обработки, что делает его особенно подходящим для работы с большими наборами данных. Тем не менее, он также имеет свои ограничения. Например, результаты алгоритма могут зависеть от начальных значений центроидов, что может привести к различным результатам при каждом запуске. Кроме того, метод требует предварительного задания количества кластеров k, что может быть затруднительно в условиях неопределенности.

Для преодоления этих ограничений исследователи разрабатывают различные модификации и улучшения алгоритма k-средних, такие как метод k-средних++ для более эффективного выбора начальных центроидов или использование методов оценки, таких как метод локтя, для определения оптимального числа кластеров. Эти усовершенствования помогают повысить точность и надежность кластеризации, что делает метод k-средних мощным инструментом для анализа данных в различных областях, включая маркетинг, биоинформатику и социальные науки.

Действие алгоритма таково, что он стремится минимизировать суммарное квадратичное отклонение точек кластеров от центров этих кластеров:

$$V = \sum_{i=1}^{k} \sum_{x \in S_i} (x - \mu_i)^2$$

где k - число кластеров, S_i - полученные кластеры, i-1, 2..., k, а μ_i - центры масс всех векторов x из кластера S_i .

Алгоритм разделительной кластеризации, также известный как метод k-средних, представляет собой подход к разбиению множества элементов в векторном пространстве на заранее заданное количество кластеров k. Данный метод относится к классу неиерархических алгоритмов кластеризации, что делает его особенно популярным в задачах, где необходимо быстро и эффективно группировать данные.

Процесс работы алгоритма можно описать как итерационную процедуру, состоящую из нескольких ключевых этапов:

1. Определение числа кластеров k: На первом этапе пользователь или исследователь задает количество кластеров, на которое необходимо разбить данные. Выбор этого параметра может зависеть от специфики задачи и предварительного анализа данных.
2. Инициализация центров кластеров: Из исходного набора данных случайным образом выбираются k записей, которые будут служить начальными центрами кластеров. Этот этап важен, так как начальные значения могут существенно повлиять на конечный результат кластеризации.
3. Присвоение записей кластерам: На следующем этапе для каждой записи из исходной выборки определяется ближайший к ней центр кластера. Это делается с использованием метрики расстояния, чаще всего евклидова расстояния. Записи, которые ближе всего к определенному центру, образуют начальные кластеры. На этом этапе происходит первичное распределение данных по кластерам.
4. Вычисление центроидов: После того как записи были распределены по кластерам, вычисляются центроиды (центры тяжести) для каждого кластера. Каждый центроид представляет собой вектор, элементы которого являются средними значениями признаков, рассчитанными по всем записям, входящим в соответствующий кластер. Затем центры кластеров обновляются, смещаясь в сторону вычисленных центроидов.
5. Итерация и сходимость: Процесс повторяется, начиная с этапа присвоения записей кластерам, до тех пор, пока границы кластеров не перестанут изменяться от итерации к итерации. Это означает, что на каждой итерации в каждом кластере будет оставаться один и тот же набор записей, что сигнализирует о сходимости алгоритма.

Алгоритм k-средних обладает рядом преимуществ, включая простоту реализации и скорость работы, что делает его подходящим для обработки больших объемов данных. Тем не менее, он также имеет свои ограничения, такие как чувствительность к выбору начальных центров и необходимость задавать количество кластеров заранее. Кроме того, алгоритм предполагает, что кластеры имеют сферическую форму и одинаковый размер, что может не всегда соответствовать реальным данным.

Для повышения устойчивости и эффективности алгоритма в практике часто применяются различные методы и техники, такие как инициализация с помощью метода k-средних, который улучшает выбор начальных центров, или использование различных метрик расстояния для более точного определения близости между записями. Таким образом, алгоритм разделительной кластеризации продолжает оставаться актуальным инструментом в области анализа данных и машинного обучения, позволяя исследователям эффективно группировать данные и выявлять скрытые закономерности [7].

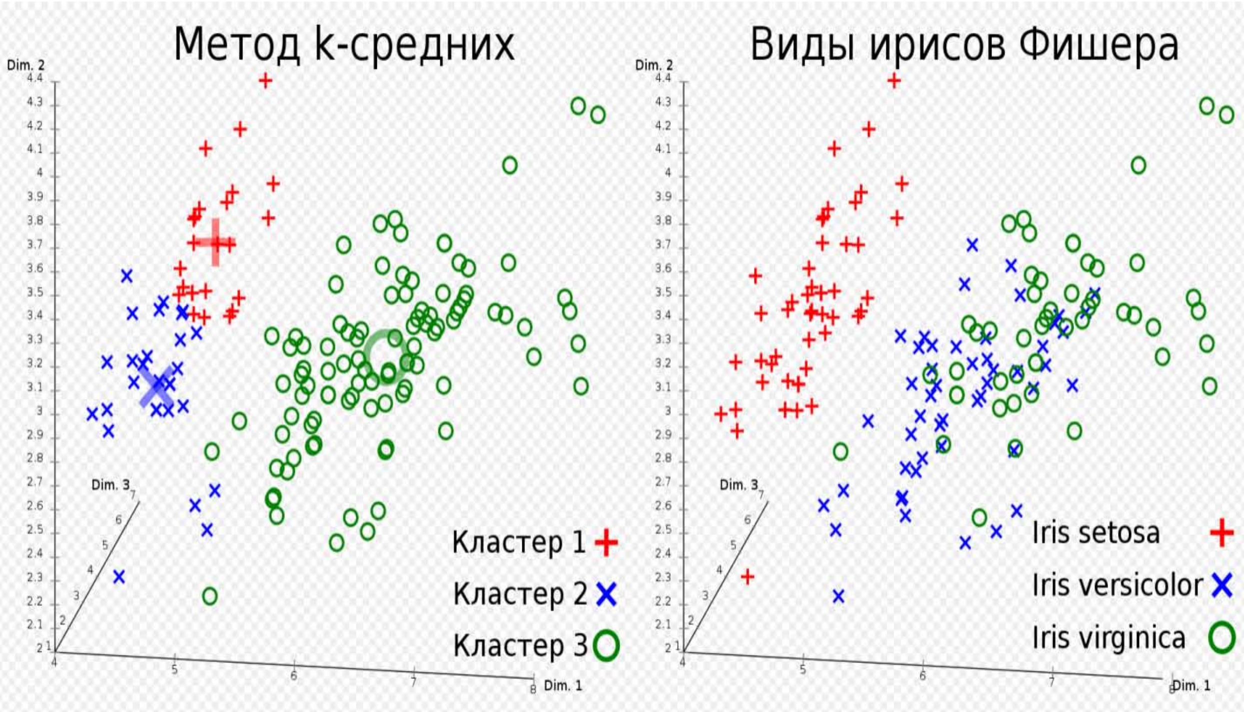

Рис. 3: Пример кластеризации методом k-средних

Одним из основных достоинств метода k-средних является его простота, которая проявляется в высокой скорости выполнения и эффективности по сравнению с другими алгоритмами кластеризации, особенно при обработке крупных наборов данных. Этот метод позволяет быстро и эффективно разделять данные на группы, что делает его особенно полезным в условиях, когда необходимо обрабатывать большие объемы информации.

Метод k-средних может служить начальным этапом для предварительного разбиения больших массивов данных на кластеры. После этого этапа можно проводить более сложный и мощный кластерный анализ подкластеров, что позволяет углубить понимание структуры данных и выявить более тонкие закономерности. Такой подход способствует более детальному изучению данных и может привести к обнаружению скрытых взаимосвязей, которые не были очевидны на первом этапе анализа [8].

Кроме того, метод k-средних может быть использован для оценки оптимального количества кластеров, что является важным шагом в процессе кластеризации. Он позволяет «прикинуть» количество кластеров, а также выявить потенциальные неучтенные данные и связи в наборах. Это особенно актуально в ситуациях, когда исследователь сталкивается с большими и сложными данными, где традиционные методы анализа могут оказаться недостаточно эффективными.

Таким образом, метод k-средних не только обеспечивает быструю и эффективную кластеризацию, но и открывает новые возможности для более глубокого анализа данных. Его применение может значительно улучшить результаты исследований в различных областях, таких как маркетинг, биоинформатика и социальные науки, где важно выявление закономерностей и структур в больших объемах информации.

VI. РАЗРАБОТКА МЕТОДИКИ АНАЛИЗА ТРАЕКТОРИИ РЕЖУЩЕГО ИНСТРУМЕНТА С ИСПОЛЬЗОВАНИЕМ РАЗРАБАТЫВАЕМОГО МОДУЛЯ

Методика анализа траектории режущего инструмента с использованием разрабаты- ваемого модуля представлена на рис. 4.

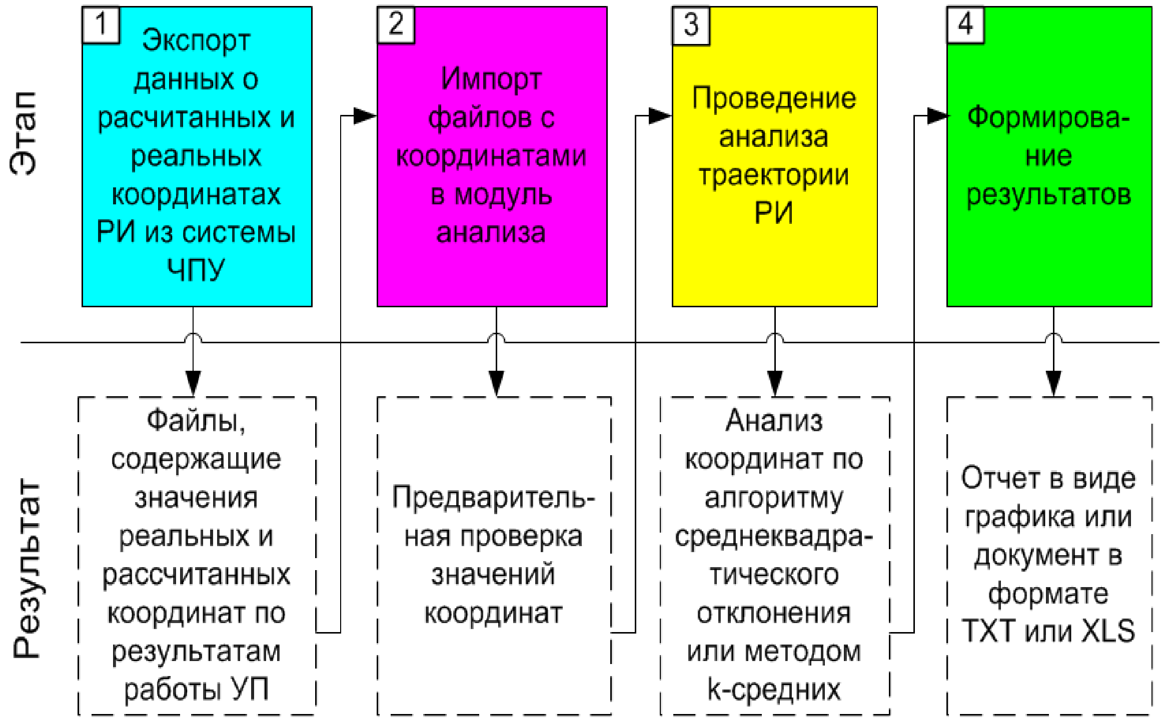

Рис. 4: Методика анализа траектории режущего инструмента с использованием разрабатываемого модуля

Первоначально осуществляется экспорт данных о рассчитанных и реальных координатах режущего инструмента из системы ЧПУ «АксиОМА Контрол». В результате этого процесса формируются текстовые файлы (*.txt), содержащие значения реальных и рассчитанных координат, полученные по итогам выполнения управляющей программы (УП). Эти координаты можно извлечь из специального режима измерений в системе ЧПУ, что позволяет получать данные за заданный промежуток времени. Важно отметить, что данные файлы извлекаются непосредственно из ЧПУ и не зависят от разрабатываемого модуля [9].

Далее происходит импорт файлов с координатами в модуль анализа. Перед дальнейшей обработкой данные проходят предварительную проверку на корректность. Система должна выявлять ошибки, возникающие из-за неправильного заполнения данных или некорректного формата файлов.

Затем осуществляется анализ траектории режущего инструмента путем вычисления отклонений, представляющих собой разницу между рассчитанными и реальными координатами. Кроме того, координаты могут быть проанализированы с использованием алгоритма среднеквадратического отклонения или метода k-средних [10].

В заключение формируется отчет, который позволяет сохранить полученные данные. Эти данные могут быть представлены в виде графиков, текстового отчета в формате *.txt или в формате XLS-файла [11].

Алгоритм работы разрабатываемого модуля анализа траектории режущего инструмента представлен на рис. 5.

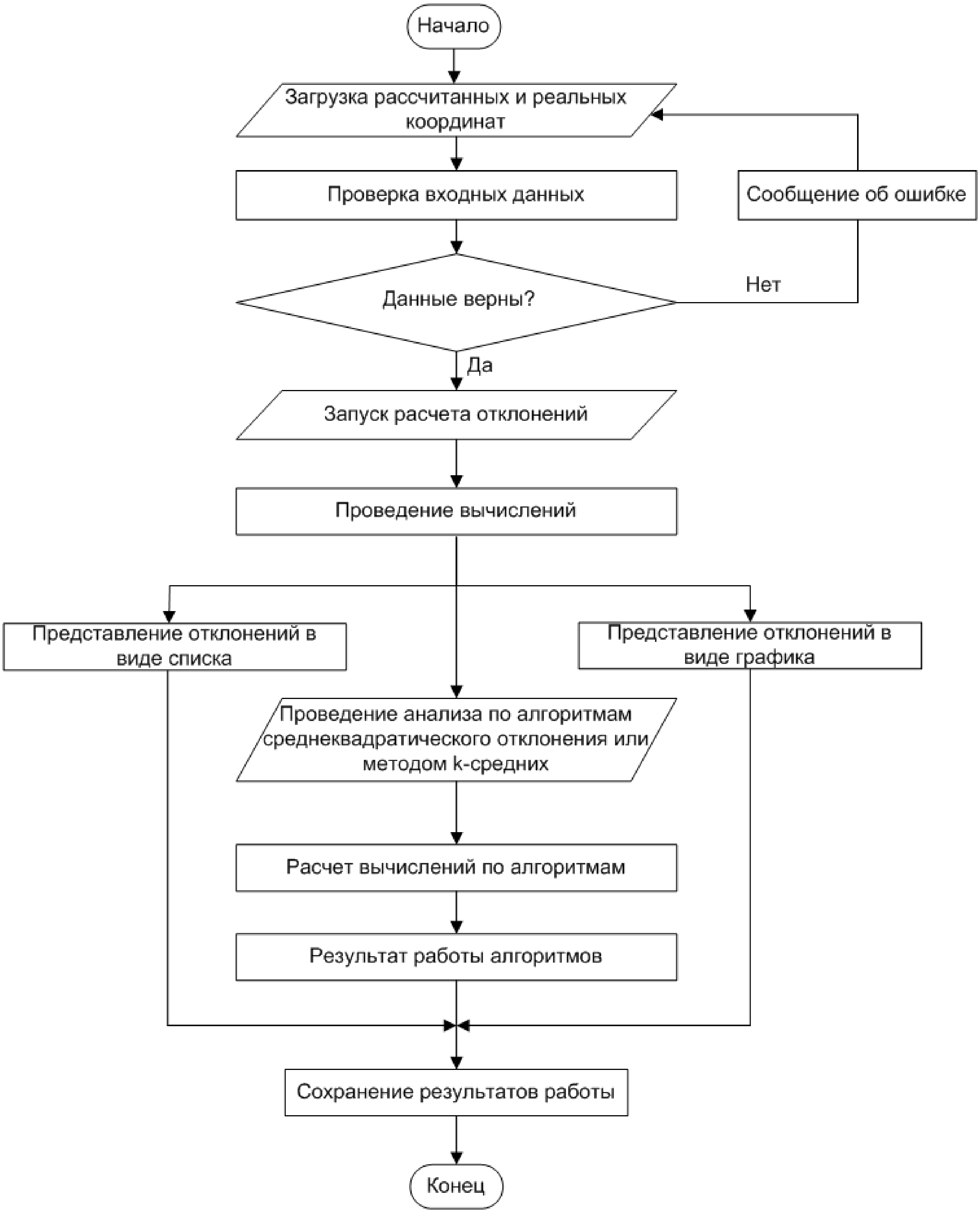

Рис. 5: Алгоритм работы разрабатываемого модуля анализа

Описание алгоритма:

1. Перед началом работы с модулем анализа пользователь должен осуществить загрузку файлов с реальными и рассчитанными координатами.
2. После чего проводится проверка входных данных на соответствие определенным требованиям, в случае если данные не корректны или же загружен не тот формат документа, то пользователь получает

уведомление об ошибке, после чего нужно заново повторить процедуру загрузки файлов либо провести редактирование в окне программы.

3. Далее пользователь путем нажатия соответствующей кнопки запускает процесс вычисления отклонений.
4. Полученные отклонения представляются в поле «Отклонения» в виде списка. При необходимости, их можно представить в виде графика.
5. Затем проводится анализ и расчет вычислений по алгоритмам среднеквадратического отклонения или методом k-средних.
6. В заключение после работы с модулем анализа следует сохранение результатов работы.

VII. ПРАКТИЧЕСКАЯ РЕАЛИЗАЦИЯ МОДУЛЯ АНАЛИЗА ТРАЕКТОРИИ РЕЖУЩЕГО ИНСТРУМЕНТА ДЛЯ СИСТЕМЫ ЧПУ «АКСИОМА КОНТРОЛ»

7.1 Выбор инструментальных средств разработки

Для разработки модуля анализа траектории режущего инструмента была выбрана среда разработки, которая называется Visual Studio Code. В ней производится редактирование начального кода, в которой можно создавать приложения, которые будут работать на нескольких системах, например, такие как WEB, или приложения с названием - облачные. Основными факторами, повлиявшими на выбор среды, являлись: бесплатность, адаптация под ОС Windows, много различных настроек всей программы и интерфейса, расширяемая библиотека дополнений и готовых решений, также редактор поддерживает большинство популярных языков, которые используются для создания приложений, а еще это простая и гибкая среда разработки. Учитывая все функции и свойства Visual Studio Code, он отлично подходит для WEB-разработки, и для разработки инструмента выбран язык программирования JavaScript, который взаимодействует и поддерживается выбранной средой [12].

Когда нужно реализовать WEB-приложение, для этой цели хорошо подходит такой язык программирования как JavaScript, он используется наиболее часто в отличие от других языков, потому что заточен на веб-разработку, также среди основных особенностей можно выделить следующие:

- Необходимость для WEB- разработки. Этот язык взаимодействует с любыми популярными браузерами и поддерживает всех их скрипты. Также присутствует взаимодействие с HTML, CSS, а также и с серверной частью.
- JavaScript за счет своей скорости, а также производительности, может в какой-то мере обрабатывать страницы на программном обеспечении (ПО) пользователя, при этом не обращаясь на сервер. Это помогает снижать нагрузку на сервер, экономит вместе с этим время, а также трафик.
- В открытом доступе имеется очень большой список уже готовых решений, поэтому при работе в JavaScript легче стало использовать библиотеки, посредством взаимодействия с ними.
- Незамысловатое, и целесообразное применение.
- Пользовательский интерфейс имеет очень удобный внешний вид. В нем присутствует заполнение формы, также есть активация разнообразных кнопок, выбор различных действий, проверка ввода данных, а еще реагирование на наведение в определенную область или, например, на клик мыши.
- Лёгкость освоения, а также опыт работы с этим языком программирования.

Программа, которая написана на JavaScript именуется как скрипт. Скрипт имеет возможность встраиваться в язык разметки HTML, и запускается автоматически, когда загружается WEB-страница, выполняется он в виде самого простого текста [13]. Для того, чтобы запустить скрипт не нужно специализированного ПО, а также не надо производить компиляцию для запуска. В этом и есть отличие JavaScript от Java. Выбранный язык может запускаться где угодно, например, в браузере или на сервере, а также на других устройствах, если оно содержит специальную программу, под названием «движок» JavaScript.

JavaScript является «безопасным», он не дает возможности низкоуровневого доступа к памяти, а также процессору, и создавался с такой целью, потому что браузеры этого не требуют [14].

Потенциал языка зависит от библиотек, которые используются в работе, в разработке модуля будет использоваться библиотека React. В браузере, когда используется JavaScript, у ПО есть связь с пользователем, а также WEB-сервером. Данный язык имеет возможность встраивать HTML (код), изменить содержимое, которое уже есть в наличии, или улучшить стиль. Реагирует на любые воздействия пользователя, которые были описаны ранее. Имеет возможность отправить сетевой запрос на удалённый сервер, скачать или загрузить различные файлы. Получить и установить cookie, задать вопросы человеку, который посетил страницу, демонстрировать различные сообщения, а также может запомнить данные, имеющиеся на стороне клиента [15].

7.2 Алгоритм функционирования процесса преобразования с использованием библиотеки функций

Загружаемые в модуль файлы представляют собой два файла в формате *.txt, которые содержат значения рассчитанных и реальных координат из системы ЧПУ «Аксиома Контрол». Файлы координат состоят из набора строк, в каждой строке содержатся данные о координатах X, Y и Z. Также, в каждой строке координата записана через пробел, значения могут быть как целые, так и десятичные. После последней координаты пробела не следует, сразу происходит переход к следующим координатам. Модуль производит проверку файла на правильный формат файла, если он не соответствует формату *.txt система выдает ошибку о неверном формате загружаемого файла. Также происходит проверка файла на корректность заполнения, например, если текстовый документ будет состоять не из цифр, который представляет собой набор координат, а текста, то в таком случае отображение будет некорректным [16].

Пример координат из текстового файла:

46,065	115,220	-18,400
47,197	115,009	-18,230
52,076	114,428	-18,060
53,294	114,428	-17,890
59,160	114,428	-17,720
…	…	…

Координаты можно записывать вручную и при необходимости редактировать, даже если файлы уже загружены в систему. Загружаются файлы с рассчитанными и реальными координатами по нажатию кнопки «Загрузить», далее выбирается файл на носителе и координаты отображаются в полях координат.

7.3 Программная реализация пользовательского интерфейса модуля анализа траектории и формирования отчетов

В главном окне интерфейса имеется две кнопки «Загрузить», по нажатию которых происходит загрузка файлов рассчитанных и реальных координат, далее производится нажатие на кнопку «Расчет» и в правом поле «Отклонение» отображаются рассчитанные отклонения. Отклонения можно сохранить по нажатию кнопки «Сохранить» [17].

По нажатию кнопки, отклонения сохраняются в формате TXT или EXCEL.

Также после расчета отклонений, нажав на кнопку «Показать график» в левом верхнем углу от панели «Рассчитанные координаты» отобразится график отклонений.

После нажатия кнопки «Показать график», появится окно с графиком отклонений, представленное на рис. 6.

Рис. 6: Окно «График отклонения»

На графике представлены отклонения по 3 осям (X, Y, Z), в автоматическом режиме происходит настройка масштаба под числа отклонений. При наведении на график отображается конкретная точка, ее номер и отклонения по X, Y и Z. Ось слева показывает численные отклонения, ось снизу показывает пронумерованные точки.

Также график можно сохранить, путем нажатия на кнопку «Скачать график», которая находится в окне самого графика отклонений.

Тестирование и отладка модуля анализа траектории режущего инструмента

Для проверки работоспособности модуля, нужно провести тестирование, посредством проведения анализа рассчитанных и реальных координат из файлов *.txt.

Нажатием на кнопку «Загрузить», загружаем два файла рассчитанных и реальных координат в формате TXT, которые появятся в полях координат. После, нажимаем кнопку «Расчет» и программа высчитывает отклонения между рассчитанными и реальными координатами, и также отображает их в поле «Отклонение», работа представлена на рис. 7. Если нужно, результаты отклонений можно сохранить в формате TXT или EXCEL.

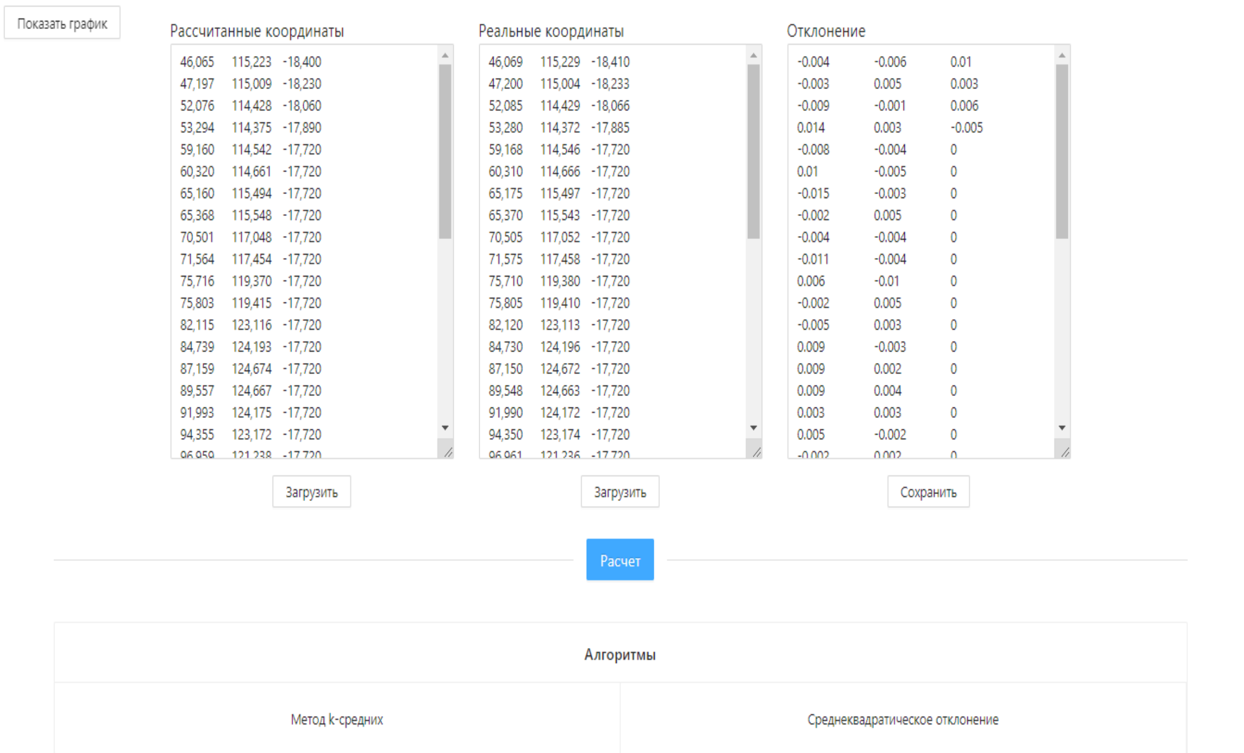

Рис. 7: Работа программы с рассчитанными отклонениями

Далее нажмем на кнопку «Показать график» на рис. 7 и проверим работоспособность отображения графика, продемонстрировано это на рис. 8. Также в окне графика имеется кнопка «Скачать график», для того чтобы проводить анализ в дальнейшем.

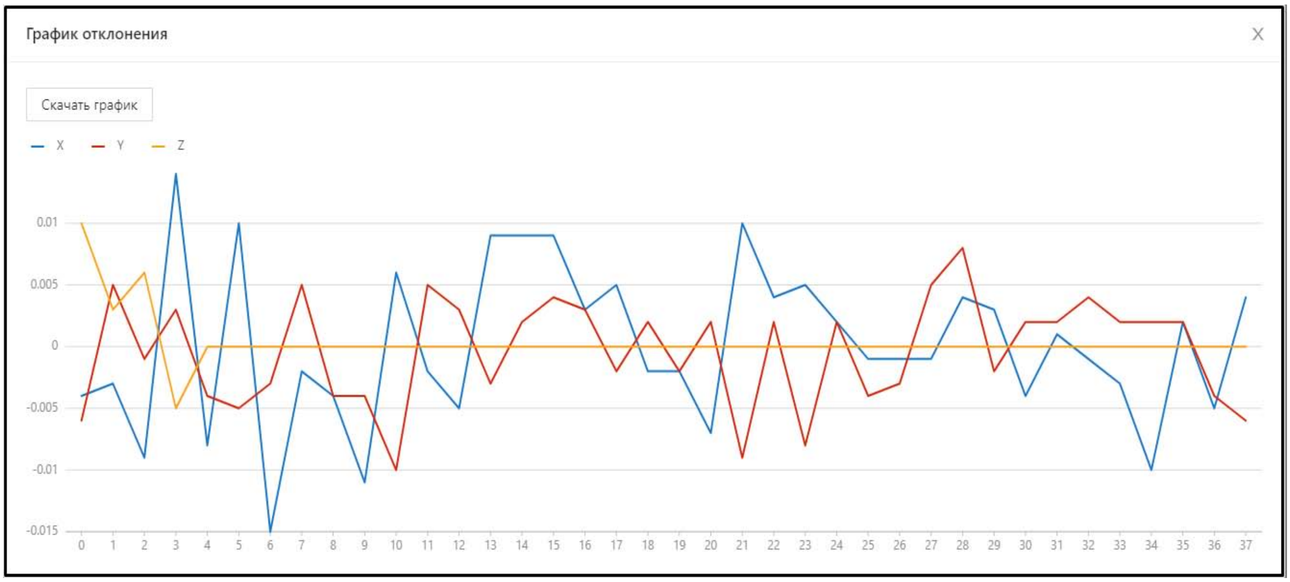

Рис. 8: Отображение графика отклонений после нажатия кнопки «Показать график»

Закроем окно графика нажав кнопку «Закрыть окно» (крестик в правом верхнем углу) представленное на рис. 8.

Вернувшись на главный экран программы, нажмем кнопку «Среднеквадратическое отклонение» в поле «Алгоритмы».

Программа отобразит окно «Среднеквадратическое отклонение», которое представлено на рис. 9.

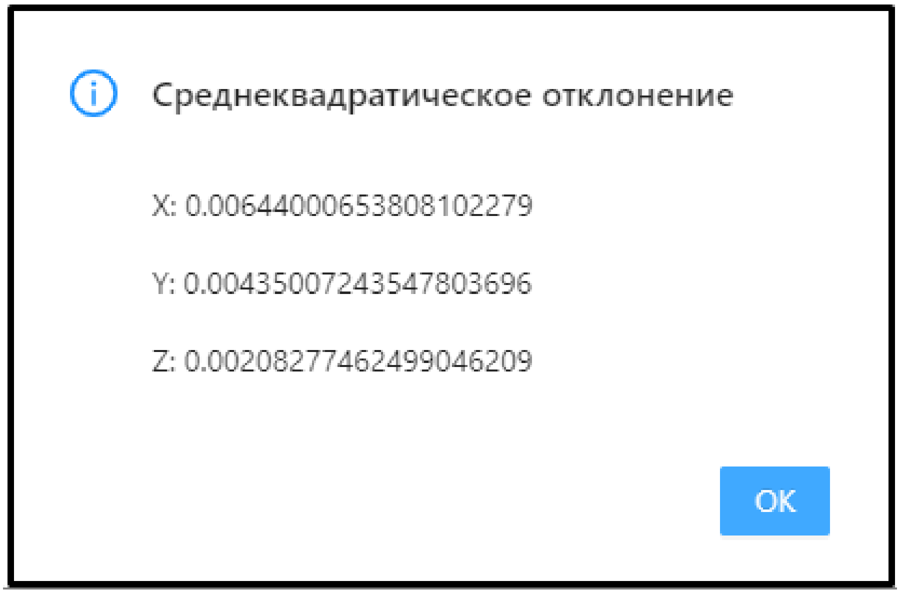

Рис. 9: Вывод алгоритма «Среднеквадратическое отклонение»

Нажимая кнопку «ОК» на рис. 9, окно закроется и будет отображен главный вид программы.

Снова, в поле «Алгоритмы», выбирается «Метод k-средних» и в результате отображается график, показанный на рис. 10.

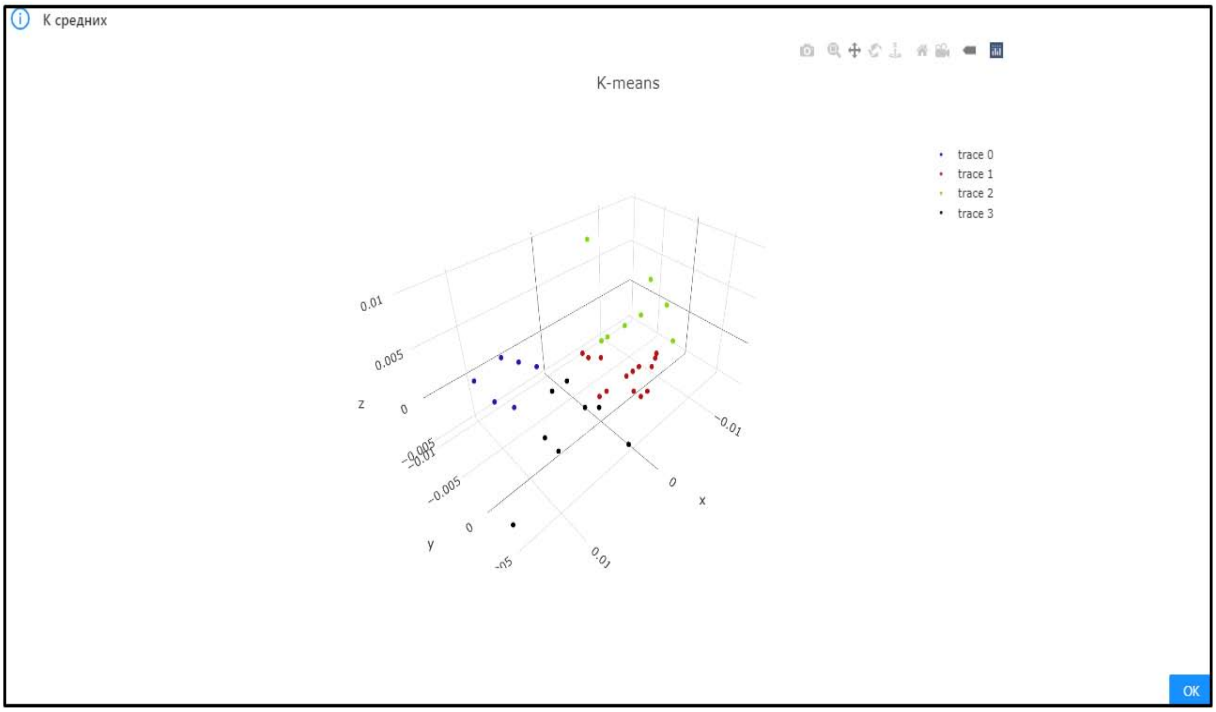

Рис. 10: Результат работы алгоритма «Метод k-средних»

Имеется возможность сохранить график на рисунке 10 в файл *.png, для дальнейшего анализа.

7.4 Тестирование работы алгоритма метода k-средних

Далее подробно тестируется алгоритм «Метод k-средних», для понимания всех аспектов работы данного алгоритма и подтверждения правильности его работоспособности.

Выборка реальных и рассчитанных координат будет максимально соответствовать реальным условиям, для этого координаты загружаются в программу и считаются отклонения. Выборка представлена на рис. 10.

Выбирается алгоритм «Метод k-средних», после отображается график, в котором проводится дальнейший анализ.

Рассчитанные координаты

46,065	115,223	-18,400
47,197	115,009	-18,230
52,076	114,429	-18,060
53,294	114,428	-17,890
59,160	114,428	-17,720
60,340	114,428	-17,720
65,161	114,428	-17,720
65,368	114,428	-17,720
70,501	114,426	-17,720
75,368	114,428	-17,720
85,368	114,428	-17,720

Реальные координаты

46,064	115,223	-18,400
47,196	115,009	-18,230
52,075	114,429	-18,060
53,294	114,428	-17,889
59,160	114,428	-17,720
60,340	114,428	-17,720
65,162	114,428	-17,720
65,368	114,428	-17,720
70,501	114,428	-17,720
75,368	114,428	-17,720
85,368	114,428	-17,720

Отклонение

0.001	0	0
0.001	0	0
0.001	0	0
0	0	-0.001
0	0	0
0	0	0
-0.001	0	0
0	0	0
0	-0.002	0
0	0	0
0	0	0

Рис. 11. Выборка реальных и рассчитанных координат

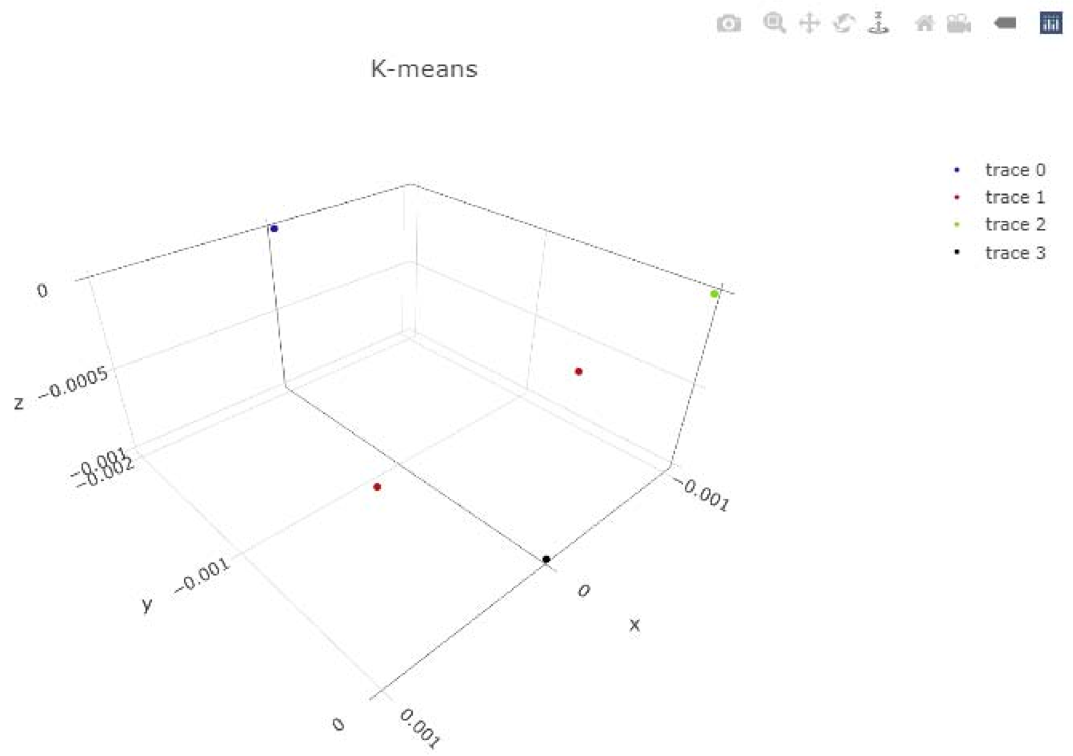

Рис. 12; Результат выполнения алгоритма «Метод k-средних»

В приведенном примере алгоритм «Метод k-средних» выявляет закономерности в отклонениях, путем проведения кластеризации данных.

Данным алгоритмом было сформировано 4 кластера:

- Trace 0 (максимальное отклонение) «Рис. 13»
- Trace 1 (остаточная группа) «Рис. 14»
- Trace 2 (единственное отрицательное отклонение по X) «Рис. 15»
- Trace 3 (единственное отклонение по Z) «Рис. 16»

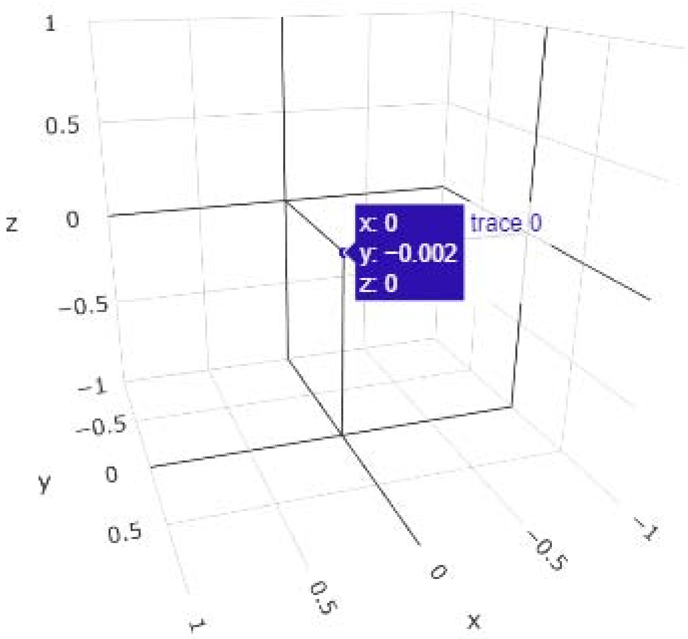

Рис. 13: Точки кластера trace0

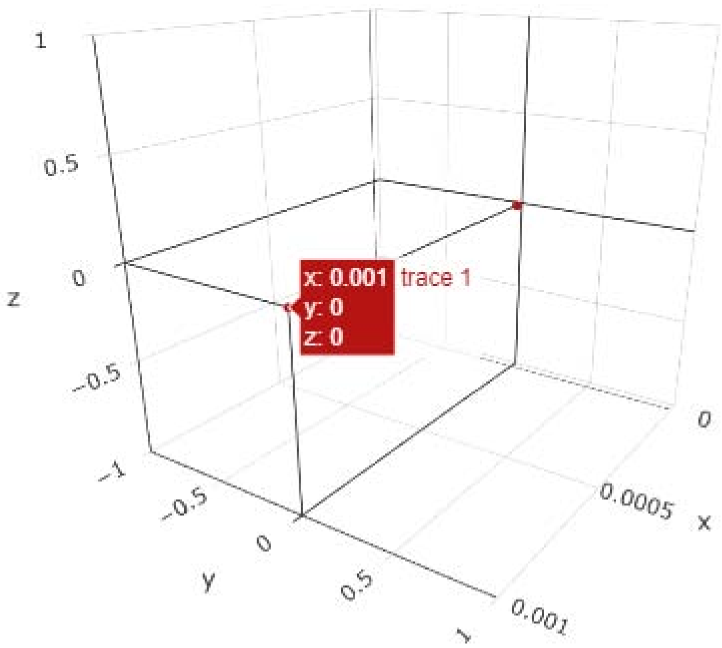

Рис. 14: Точки кластера trace1

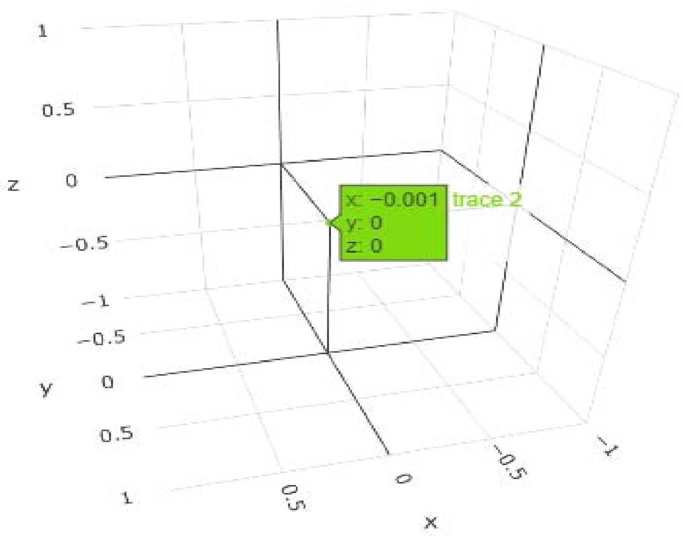

Рис. 15: Точки кластера trace2

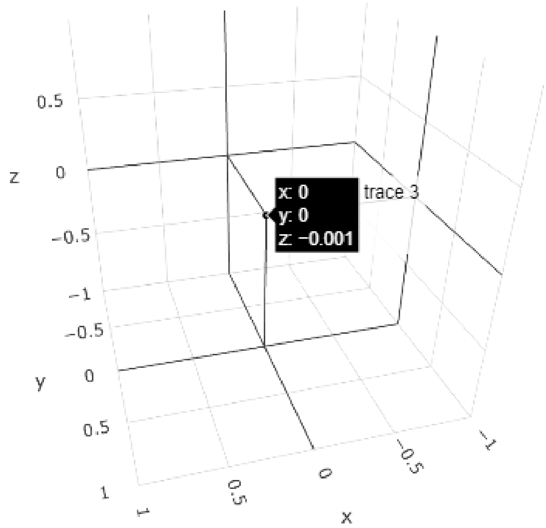

Рис. 16: Точки кластера trace3

«k-средних» — это алгоритм машинного обучения, его работа скрыта от пользователя, не всегда понятно, по каким признакам происходит кластеризация данных. Поэтому результаты работы алгоритма с различными результатами отклонений и их комбинаций, может приводить к тому, что каждый раз разбиение отклонений на группы алгоритмом, будет проводиться по другим общим признакам, которые не похожи на предыдущие.

Можно сделать вывод, что чем ярче выражен общий признак у посчитанных отклонений, тем легче формируются кластеры. Следовательно, если общие признаки выражено слабо, то алгоритму тяжелее сформировать кластеры (что выявилось в примере, а именно: группа отклонений кластера Trace1, сформирована обособленной и внутри имеет деление на 2 группы отклонений, которые по своим признакам не смогли сгруппироваться с другими кластерами отклонений, и были сгруппированы друг с другом, поэтому, в результате чего появился 4 кластер), а пользователю сложнее провести оценку полученных данных.

При сверхбольшом количестве входных данных, может потребоваться расширение кластеров, но поставлено ограничение в 4 кластера, как оптимальное.

VIII. ЗАКЛЮЧЕНИЕ

В результате проведенной работы было успешно разработано решение для анализа траектории перемещения режущего инструмента в системе ЧПУ «АксиОМА Контрол». Анализ, проведенный в рамках исследования, показал, что многие существующие системы ЧПУ не реализуют предложенные функциональные возможности, что существенно ограничивает их способность к полноценному анализу процессов обработки. Это открывает новые перспективы для улучшения и оптимизации данных систем.

В процессе работы была создана структурная схема, которая наглядно демонстрирует основные элементы системы и их взаимодействие. Данная схема позволяет визуализировать процесс загрузки файлов в разрабатываемый модуль анализа и описывает внутренние механизмы взаимодействия модулей между собой. Кроме того, она иллюстрирует, как результаты анализа данных выводятся в различные форматы отчетов, включая графики и файлы форматов *.txt и *.xls. Это обеспечивает удобство и доступность полученной информации для пользователей.

Также была разработана диаграмма прецедентов, в которой представлены ключевые возможности инструмента для анализа. Эта диаграмма служит важным инструментом для понимания функционала системы и позволяет более эффективно использовать возможности модуля.

Таким образом, результаты данной работы не только подтверждают необходимость внедрения новых функций в системы ЧПУ, но и закладывают основу для дальнейших исследований и разработок в этой области. Реализация предложенных решений позволит значительно повысить эффективность и точность обработки материалов, что, в свою очередь, будет способствовать улучшению качества продукции и оптимизации производственных процессов. В будущем, дальнейшее развитие модуля анализа может привести к созданию более совершенной и конкурентоспособной системы ЧПУ «АксиОМА Контрол», что откроет новые горизонты для пользователей и производителей в сфере числового программного управления.

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Santiago María Reyna, Agustina Bonini, Paula Lorena Bonillo, Eduardo Alberto Antonio Melano, Teresa María Reyna, Fabián Andrés Fulginiti & María Lábaque

Universidad Nacional de Córdoba (UNC)

ABSTRACT

This research presents a comprehensive methodology for the technical and environmental assessment of the refurbishment and modernization of existing hydroelectric plants in the province of Córdoba (Argentina) to use pumped storage hydropower (PSH) systems. The study is based on leveraging existing civil infrastructure, with the goal of minimizing environmental impacts, optimizing economic resources, and improving provincial energy management.

The proposed methodology combines technical, hydrological, environmental, and water resource management criteria to prioritize sites with high conversion feasibility. Of the total number of plants analyzed, four were identified as having favorable conditions: Fitz Simon, Cassaffousth, Los Molinos I, and La Viña. Field campaigns and specific analyses were subsequently conducted to assess the technical and operational feasibility of their refurbishment and modernization. The results show that the selected plants have high potential to operate with pumped storage energy storage schemes, contributing to the integration of intermittent renewable energy and strengthening the provincial electricity grid.

Keywords: hydroelectric power, pumped storage, hydropower station modernisation, energy storage, infrastructure refurbishment.

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Refurbishment and Conversion to Pumped/Storage Systems of Hydroelectric Power Plants in Córdoba (Argentina)

Rehabilitación y Conversión de Centrales Hidroeléctricas Existentes en Córdoba (Argentina) a Sistemas de Turbinado-Bombeo

Santiago María Reyna[α], Agustina Bonini[σ], Paula Lorena Bonillo[ρ], Eduardo Alberto Antonio Melano[Ѡ], Teresa María Reyna[¥], Fabián Andrés Fulginiti[§] & María Lábaque[χ]

RESUMEN

Esta investigación presenta una metodología integral para la evaluación técnica y ambiental de la refuncionalización y modernización de centrales hidroeléctricas existentes en la provincia de Córdoba (Argentina) hacia sistemas de bombeo reversible (Pumped Storage Hydropower, PSH). El estudio parte del aprovechamiento de la infraestructura civil ya instalada, con el objetivo de minimizar impactos ambientales, optimizar recursos económicos y mejorar la gestión energética provincial.

La metodología propuesta combina criterios técnicos, hidrológicos, ambientales y de gestión del recurso hídrico para priorizar sitios con alta factibilidad de conversión. De un total de centrales analizadas, se identificaron cuatro con condiciones favorables: Fitz Simon, Cassaffousth, Los Molinos I y La Viña. Posteriormente, se realizaron campañas de campo y análisis específicos para evaluar la viabilidad técnico-operativa de su reconversión y modernización. Los resultados evidencian que las centrales seleccionadas poseen un alto potencial para operar en esquemas de almacenamiento energético a partir de bombeo reversible, contribuyendo a la integración de energías renovables intermitentes y al fortalecimiento de la red eléctrica provincial.

El caso de la Central La Viña se presenta en detalle, dado su proceso actual de modernización, destacándose la oportunidad técnica y económica de incorporar la función de bombeo reversible en simultáneo con la actualización de equipamiento.

Palabras clave: energía hidroeléctrica, turbinado-bombeo, modernización de centrales hidroeléctricas, almacenamiento energético, refuncionalización de infraestructura.

ABSTRACT

This research presents a comprehensive methodology for the technical and environmental assessment of the refurbishment and modernization of existing hydroelectric plants in the province of Córdoba (Argentina) to use pumped storage hydropower (PSH) systems. The study is based on leveraging existing civil infrastructure, with the goal of minimizing environmental impacts, optimizing economic resources, and improving provincial energy management.

The proposed methodology combines technical, hydrological, environmental, and water resource management criteria to prioritize sites with high conversion feasibility. Of the total number of plants analyzed, four were identified as having favorable conditions: Fitz Simon, Cassaffousth, Los Molinos I, and La Viña. Field campaigns and specific analyses were subsequently conducted to assess the technical and operational feasibility of their refurbishment and modernization. The results show that the selected plants have high potential to operate with pumped storage energy

storage schemes, contributing to the integration of intermittent renewable energy and strengthening the provincial electricity grid.

The case of the La Viña Power Plant is presented in detail, given its current modernization process, highlighting the technical and economic opportunity of incorporating the reversible pumping function simultaneously with the equipment upgrade.

Keywords: hydroelectric power, pumped storage, hydropower station modernisation, energy storage, infrastructure refurbishment.

Author α σ ρ ¥ § χ: Facultad de Ciencias Exactas, Físicas y Naturales (FCEFyN) - Universidad Nacional de Córdoba (UNC).
Ѡ: Empresa Provincial de Energía de Córdoba (EPEC).

I. INTRODUCCIÓN

La incorporación de sistemas de almacenamiento energético es un requisito técnico indispensable para aumentar la penetración de fuentes renovables variables en los sistemas eléctricos modernos. En este contexto, el almacenamiento hidroeléctrico por bombeo reversible (*Pumped Storage Hydropower*, PSH) representa la tecnología más madura, eficiente y de mayor capacidad a nivel mundial (Simon et al., 2023).

En la provincia de Córdoba (Argentina), el sistema hidroeléctrico provincial cuenta con una serie de centrales de mediana escala construidas entre las décadas de 1940 y 1980 (ver ubicación en la Figura 1), que actualmente presentan subutilización de su capacidad instalada debido a restricciones hidrológicas, de operación y obsolescencia. Este escenario motivó el desarrollo de un proyecto de investigación orientado a evaluar la factibilidad técnica, ambiental y económica de refuncionalizar y modernizar dichas centrales hacia esquemas de turbinado-bombeo.

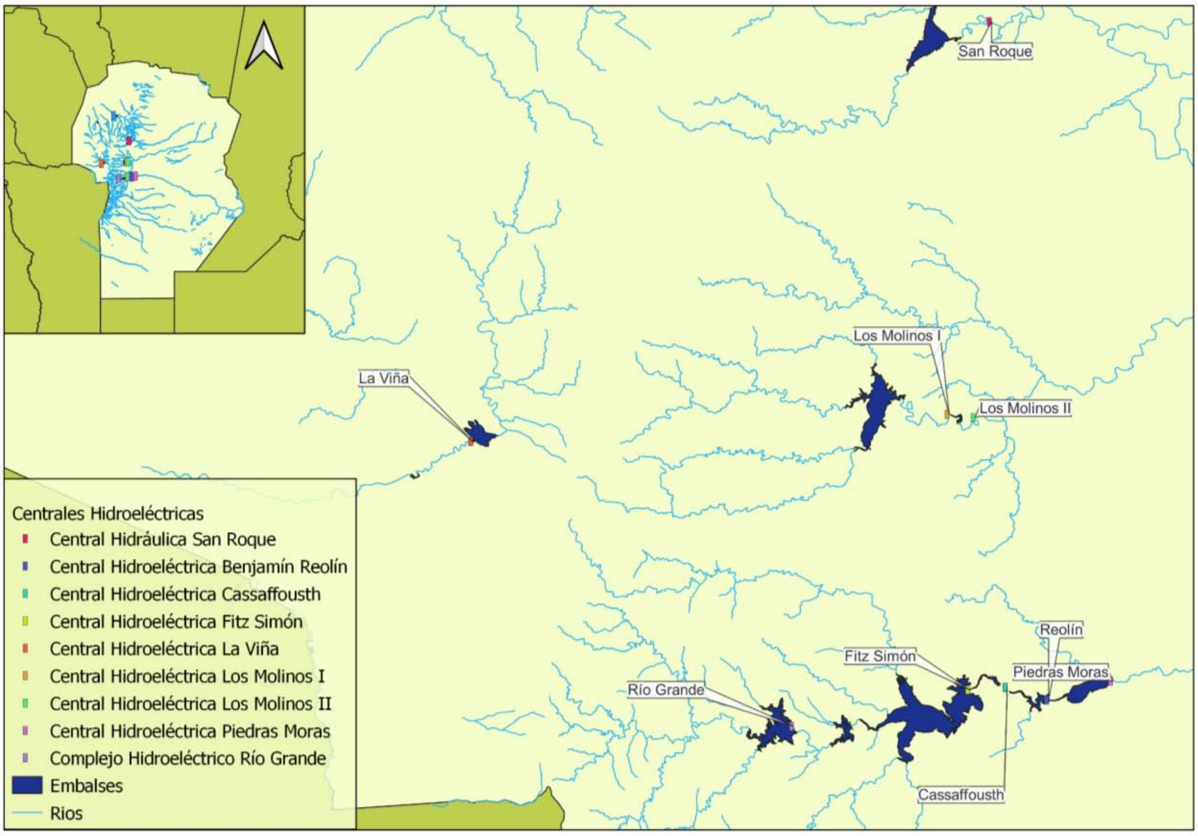

Figura 1: Embalses y centrales de la provincia de Córdoba. Fuente: Bonillo, Reyna et al., 2024

infraestructura civil disponible y minimizando nuevas intervenciones.

II. METODOLOGÍA DE EVALUACIÓN

2.1 Criterios de Selección

La metodología de selección se estructuró en torno a siete criterios principales:

1. *Infraestructura civil preexistente:* Se priorizaron centrales con estructuras que, en general, estén en buen estado de conservación (presa, casa de máquinas, líneas de transmisión y obras de conducción), minimizando la necesidad de nuevas obras y los impactos ambientales asociados.
2. *Proximidad entre embalses:* Se consideró la existencia de embalses superior e inferior. En caso de ausencia de embalse inferior, se evaluó la factibilidad de construir un azud o dique de restitución para generar el volumen de entretenimiento necesario.
3. *Elementos de disipación de sobrepresión:* Inicialmente, se consideró relevante la existencia de una chimenea de equilibrio. Sin embargo, los resultados posteriores mostraron que basta con disponer de estructuras adecuadas de descarga o alivio de sobrepresión, por lo que la presencia de chimenea no constituye un factor excluyente.
4. *Tipo de turbina y años de operación:* Se otorgó prioridad a las centrales con turbinas tipo Francis, debido a su mayor compatibilidad con esquemas reversibles. No obstante, se verificó que los equipos instalados en la mayoría de las centrales cordobesas habían alcanzado el fin de su vida útil, por lo que la sustitución de los grupos podría resultar inevitable en escenarios de modernización.
5. *Propósito del embalse:* Si bien los embalses multipropósito pueden presentar limitaciones en su régimen operativo, se identificó que la incorporación de bombeo puede optimizar la gestión del recurso al aumentar las horas de turbinado y mejorar el aprovechamiento hídrico, dado que el volumen destinado al almacenamiento por bombeo es significativamente menor al de otros usos prioritarios (agua potable, riego, control de crecidas).
6. *Factor de carga:* Las centrales con bajo factor de carga fueron consideradas candidatas prioritarias, dado que la incorporación de almacenamiento por bombeo permite incrementar la energía entregada y estabilizar su régimen de operación. Las plantas que operan en punta, con conducciones de mayor sección, presentan además una mejor predisposición hidráulica para incorporar el modo de bombeo.
7. *Condición estructural y accesibilidad:* Se incluyó una revisión de planos, inspección visual y evaluación del entorno para estimar la complejidad constructiva y logística de las obras requeridas.

2.2 Selección Preliminar

Aplicando los criterios anteriores, se identificaron como centrales con alta factibilidad de refuncionalización: *La Viña (Río de Los Sauces) (Figura 2 y 3), Los Molinos I (Río Los Molinos) (Figura 4 y 5), Fitz Simon (Sistema de Río Tercero) (Figura 6 y 7) y Cassaffousth (Sistema de Río Tercero) (Figura 7 y 8).* Estas instalaciones comparten características favorables según los criterios de selección indicados en la sección anterior: infraestructura robusta, accesibilidad, redes eléctricas de media tensión cercanas y embalses operativos que se resumen en la Tabla 1. Si bien estas centrales presentan condiciones técnicamente viables para su refuncionalización, cada una posee particularidades y desafíos específicos en relación con la infraestructura existente, el régimen hidráulico y la compatibilidad con la operación reversible. En la sección "Evaluaciones específicas y estudios de campo" se presenta la información relevada y análisis sobre los tres sistemas.

Tabla 1: Parámetros técnicos y evaluación de factibilidad para la refuncionalización a turbinado-bombeo

Parámetro	Central La Viña	Central Los Molinos I	Central Fitz Simon	Central Cassaffousth
Salto neto (m)	96	254	41,1	38,8
Caudal medio disponible (m^3/s)	5,5	7	27,6	27,6
Potencia instalada actual (MW)	16	52	10,8	15
Tipo de turbina actual	Francis de eje vertical	Francis de eje vertical	Francis de eje vertical	Francis de eje vertical
Año de instalación	1959 (Actualmente en modernización)	1957 (No ha sido objeto de modernización tecnológica sustancial)	1943 (No ha sido objeto de modernización tecnológica sustancial)	1953 (Ha tenido reparaciones recientes en el Grupo N°1 - rebobinado)
Estado de la infraestructura civil e hidráulica	Deficiente (se encuentra en tareas de reparación)	Regular (Infraestructura civil aprovechable, requiere modernización de equipos y sistemas de control).	Regular (Infraestructura civil en buenas requiere modernización de de equipos y sistemas de control).	Regular (Conducciones forzadas en buen estado, requiere modernización en sistemas de control).
Existencia de embalse inferior	La descarga inmediata es sobre un azud de restitución sin capacidad de regulación.	Dique La Quintana.	Embalse Segunda Usina Ing. Cassaffousth	Embalse Tercera Usina Ing. Benjamín Reolín.
Volumen útil del embalse superior a cota labio de vertedero (hm^3)	183 hm^3	307 hm^3	560 hm^3	560 hm^3
Presencia de estructuras para descargar sobrepresión	2 descargadores de sobrepresión por golpe de ariete.	Una chimenea de equilibrio cilíndrico de tipo diferencial.	El vástago hueco en la válvula de la obra de toma.	Una chimenea de equilibrio de tipo diferencial.
Factor de carga actual (%)	22	22	61	45

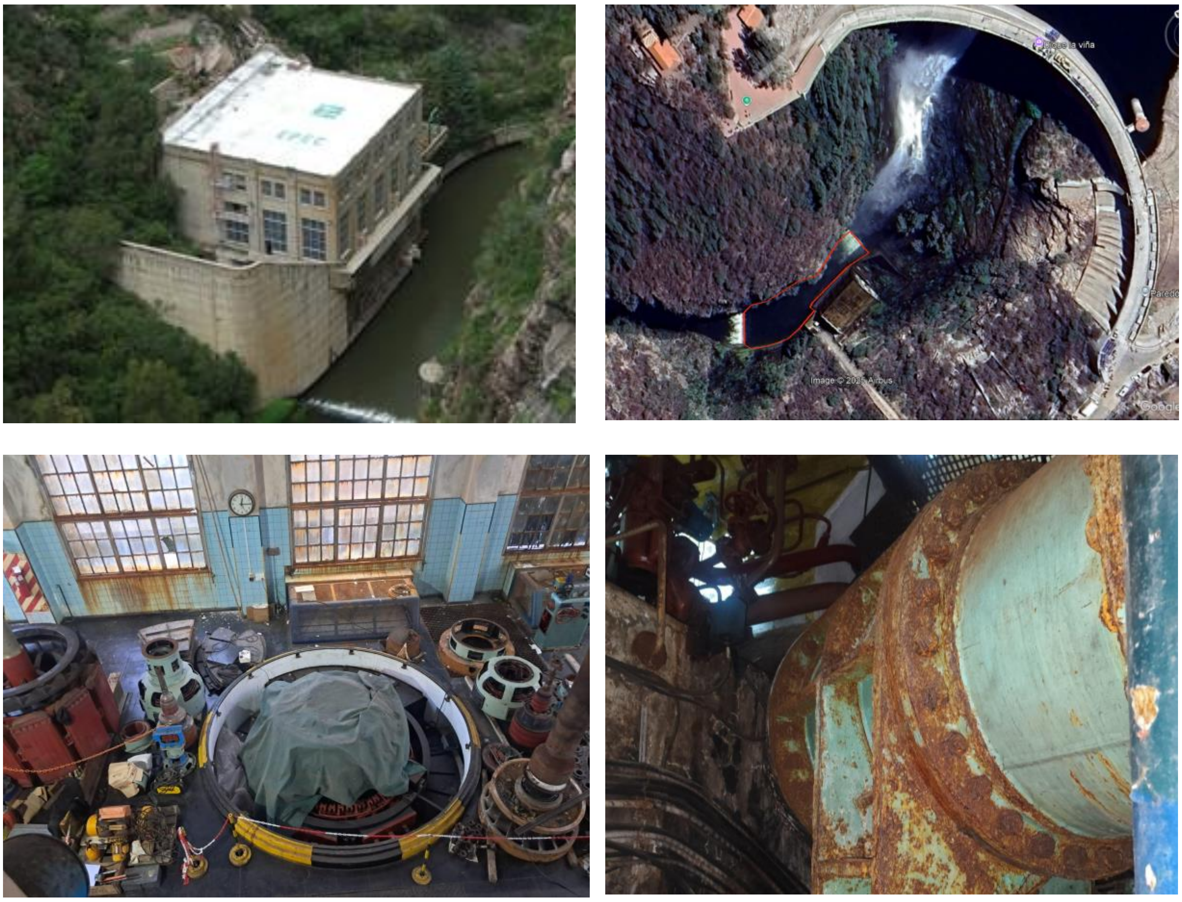

Figura 2: Central Hidroeléctrica La Viña

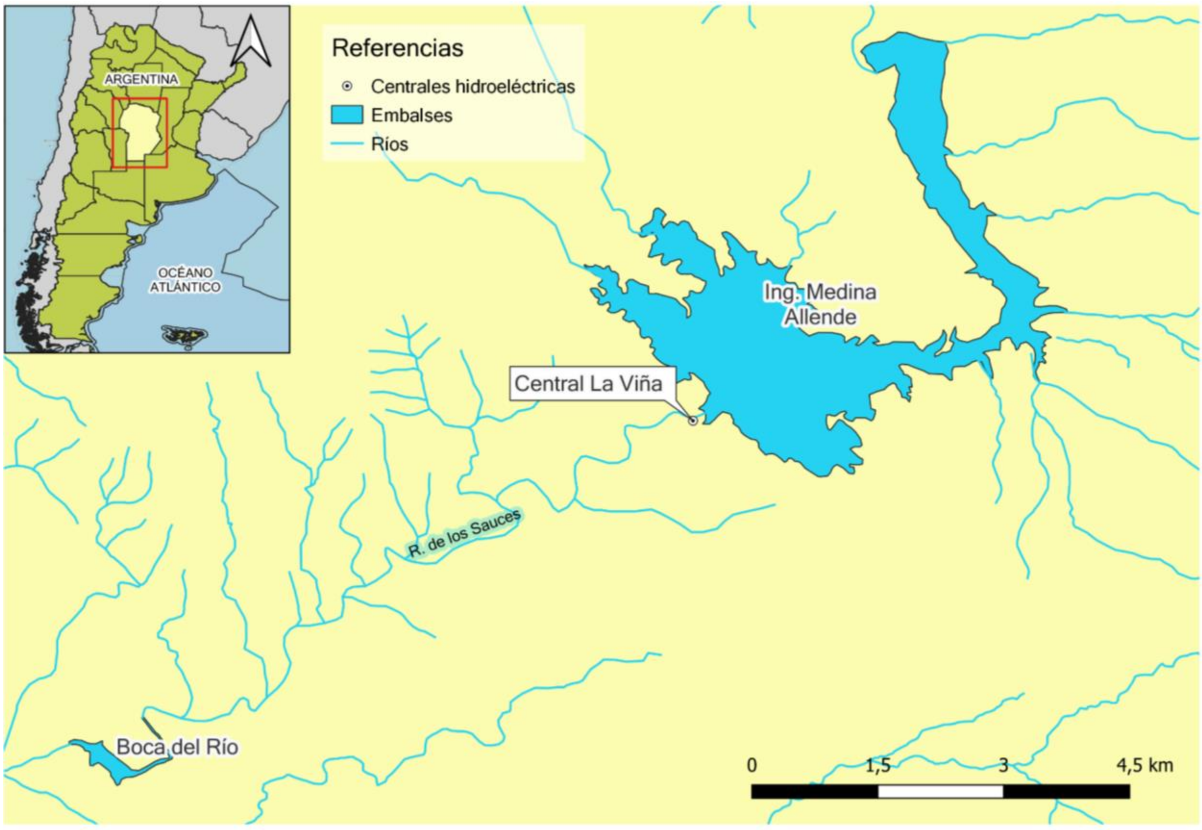

Figura 3: Ubicación geográfica del Embalse Medina Allende (Dique La Viña)

Figura 4: Central Hidroeléctrica Los Molinos I

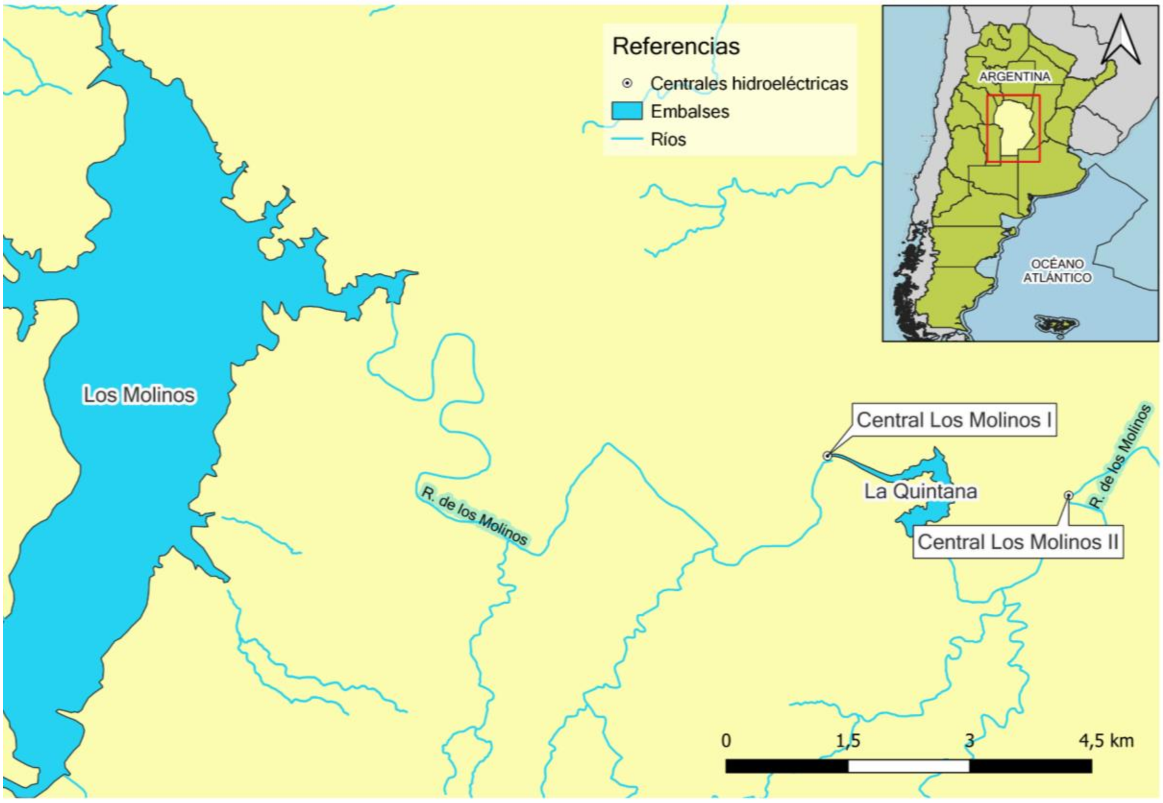

Figura 5: Ubicación geográfica del Sistema Los Molinos

Figura 6: Central Hidroeléctrica Fitz Simon

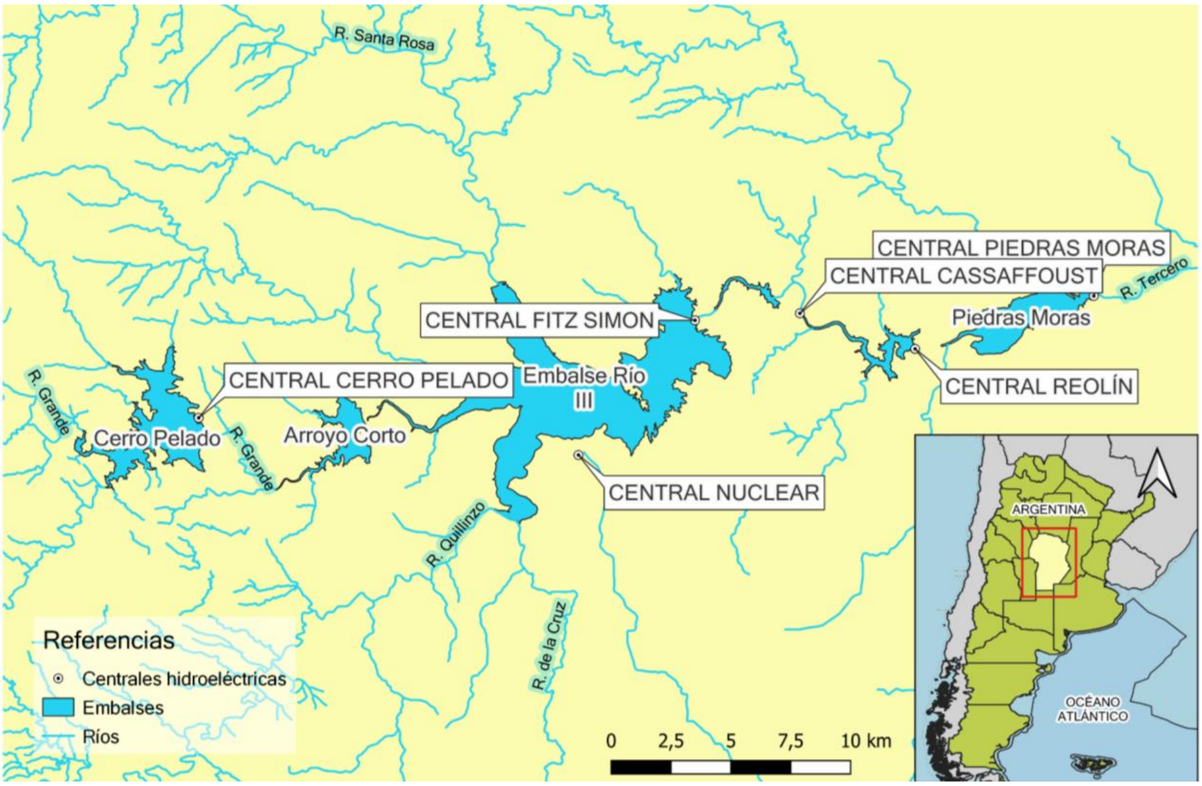

Figura 7: Ubicación geográfica del Sistema Río Tercero (en cascada: Fitz Simon, Cassaffousth y Reolín)

Figura 8: Central Hidroeléctrica Cassaffousth

III. EVALUACIONES ESPECÍFICAS Y ESTUDIOS DE CAMPO

Tras la preselección, se llevó a cabo la etapa de relevamiento y sistematización de la información disponible de las centrales (Los Molinos I, La Viña, Fitz Simon, Cassaffousth y Reolín), complementada con visitas técnicas a cada una de ellas. Esta fase permitió recopilar los datos necesarios para desarrollar las propuestas de refuncionalización y modernización. Estas alternativas contemplaron diferentes configuraciones hidráulicas y electromecánicas posibles, considerando las condiciones actuales de cada sitio, la disponibilidad de infraestructura existente y las restricciones operativas asociadas. En todos los casos se deberán actualizar los sistemas de control y automatización, sistemas de control y manejo hidráulico y verificar la sumergencia necesaria para evitar cavitación al bombear.

3.1 Central Los Molinos I

La alternativa técnica evaluada consistió en mantener las turbinas actuales y ampliar la casa de máquinas (ver Figura 10) para construir una sala de bombeo en pozo, a fin de garantizar el NPSH (*Net Positive Suction Head*) de las bombas. Se descartó elevar el nivel del embalse inferior (Dique La Quintana) por razones estructurales: el dique que debería recrecerse es mixto, conformado por un tramo de gravedad, un tramo de escollera y un vertedero tipo Creager y se deberían aplicar técnicas diferentes en cada tramo. Además, presenta problemas operativos en sus compuertas, lo que haría mucho más costosa su intervención para aumentar su altura.

El pozo de bombeo se conectaría hidráulica y eléctricamente a la central existente para permitir el bombeo de agua desde el embalse inferior al superior a través de las tuberías forzadas y túneles existentes (un ejemplo de un proyecto similar de refuncionalización es la central en Sloy, Escocia (SSE Renewables, 2025) que se puede ver en la Figura 11).

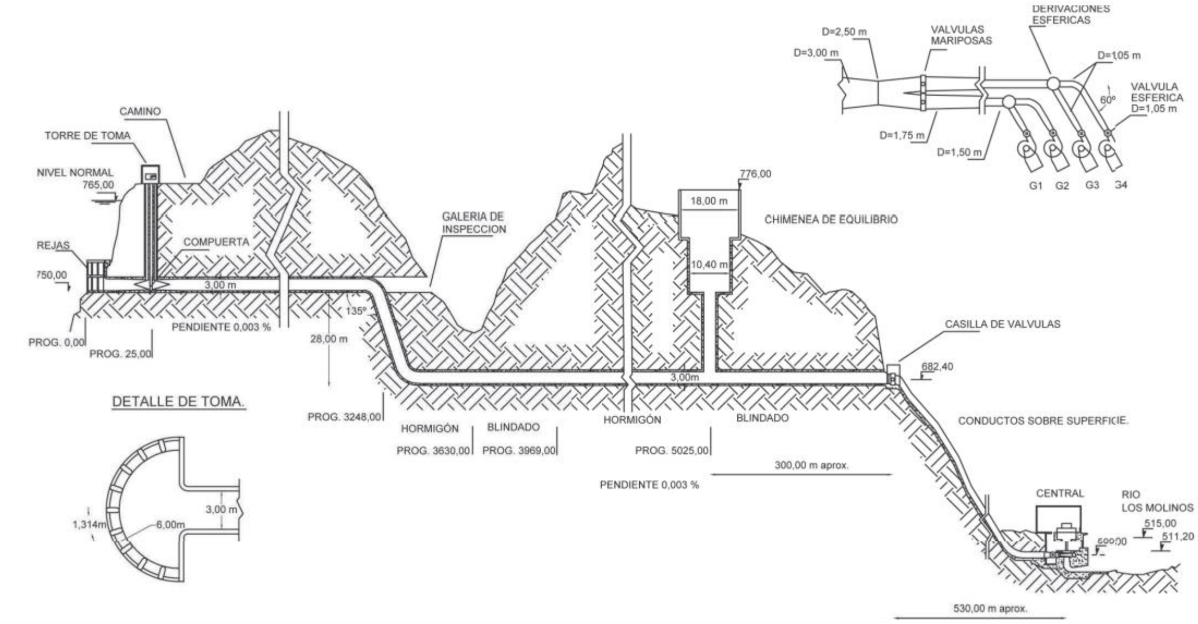

Figura 9: Esquema de turbinado actual Los Molinos I (López y Rodríguez, 2011)

Figura 10: Lugar para la ampliación de la casa de máquinas Central Los Molinos I

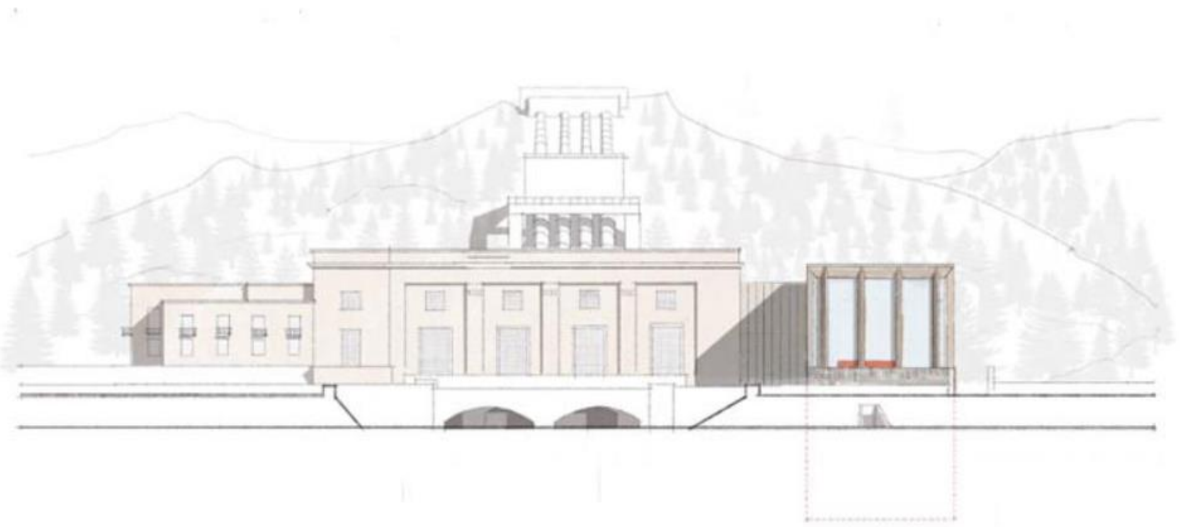

Figura 11: Esquema del proyecto de ampliación de la central de Sloy, Escocia. La casa de máquinas nueva, que albergaría las bombas, se encuentra a la derecha de la casa original

3.2 Central Fitz Simon

La propuesta consistió en construir un azud de restitución (Figura 13) y adaptar los rodetes actuales a operación reversible, manteniendo las conducciones hidráulicas existentes. Este esquema permitiría minimizar costos y aprovechar la infraestructura en funcionamiento, incorporando un nuevo sistema de control automatizado y sincronizado con la red provincial.

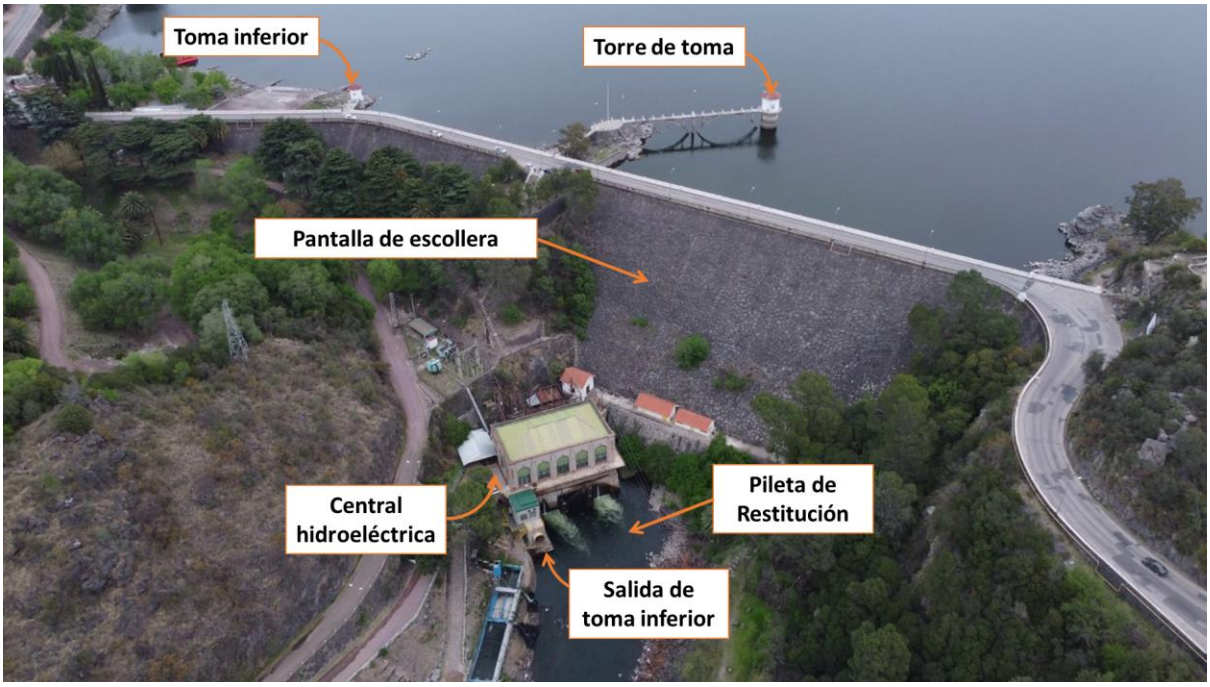

Figura 12: Componentes del Sistema Hidroeléctrico Fitz Simon

Figura 13: Modificación Prevista de la Restitución de la Central Hidroeléctrica Fitz Simon

3.3 Central Cassaffousth

Al igual que en la central aguas arriba (Fitz Simon), la propuesta consistió en recrecer el azud de restitución actual (Figura 15) y adaptar los 3 grupos (rodete y generador) actuales a operación reversible, manteniendo las conducciones hidráulicas existentes. Este esquema permitiría minimizar costos y aprovechar la infraestructura en funcionamiento, incorporando un nuevo sistema de control automatizado y sincronizado con la red provincial.

Figura 14. Componentes del Sistema Hidroeléctrico Cassaffousth

Figura 15: Modificación Prevista de la Restitución de la Central Hidroeléctrica Cassaffousth

3.4 Central La Viña

La central La Viña fue seleccionada como caso piloto debido a su estado operativo, condiciones hidráulicas y proceso actual de modernización. La central en 2020 alcanzó un grado crítico de deterioro estructural y funcional con deficiencias significativas en obras de toma y conducción por lo que se recurrió a su modernización. Aun cuando, en el caso de La Viña, existe un embalse compensador aguas abajo, este no podría cumplir el rol de embalse inferior para contener el volumen de entretenimiento por encontrarse a gran distancia (más de 10 km aguas abajo). Para adaptarla a turbinado/bombeo, se planteó la construcción de un pequeño azud aguas abajo (Figura 16) para generar el volumen de entretenimiento necesario y garantizar el NPSH de las bombas en modo de aspiración. La propuesta técnica consistió en:

- Convertir el grupo N°1 en máquina/sistema reversible, manteniendo el grupo N°2 como generador convencional de base.
- Operar ambos grupos en régimen coordinado, permitiendo el bombeo en horas valle y el turbinado en horas pico, optimizando la gestión energética diaria.

Figura 16: Modificación prevista de la restitución de la central hidroeléctrica La Viña

IV. CASO LA VIÑA: DIAGNÓSTICO Y OPORTUNIDAD DE REFUNCIONALIZACIÓN

La central La Viña, ubicada sobre el río de los Sauces, posee actualmente una potencia instalada de 16 MW (dos turbinas Francis de 8 MW). Durante el proceso de modernización iniciado por la Empresa Provincial de Energía de Córdoba (EPEC), se registraron dos hallazgos críticos:

- El caudal de diseño histórico de 7 m³/s (Agua y Energía Eléctrica, 1969) resultó mayor respecto al caudal medio medido entre 1995 y 2019 de aproximadamente 5,5 m³/s (Guida y Guillén, 2019), indicando una posible reducción del recurso hídrico asociada a variabilidad climática.
- El nivel operativo del embalse se mantuvo por debajo del nivel de diseño (estando, en promedio unos 10 m bajo el labio del vertedero). Esto, debido a conflictos con regantes aguas abajo y a ineficiencias en los sistemas de riego tradicionales (por gravedad y surcos).

La primera propuesta de modernización contempló anular el grupo N°1 y reemplazar el grupo N°2 (Figura 17) por una unidad de menor potencia (6 MW) con mayor factor de utilización (≈20 h/día). El presente estudio propuso una alternativa más eficiente, con un mayor aprovechamiento de la obra civil e hidráulica: instalar en el Grupo N°1 una turbina reversible, manteniendo el Grupo N°2 como generador convencional.

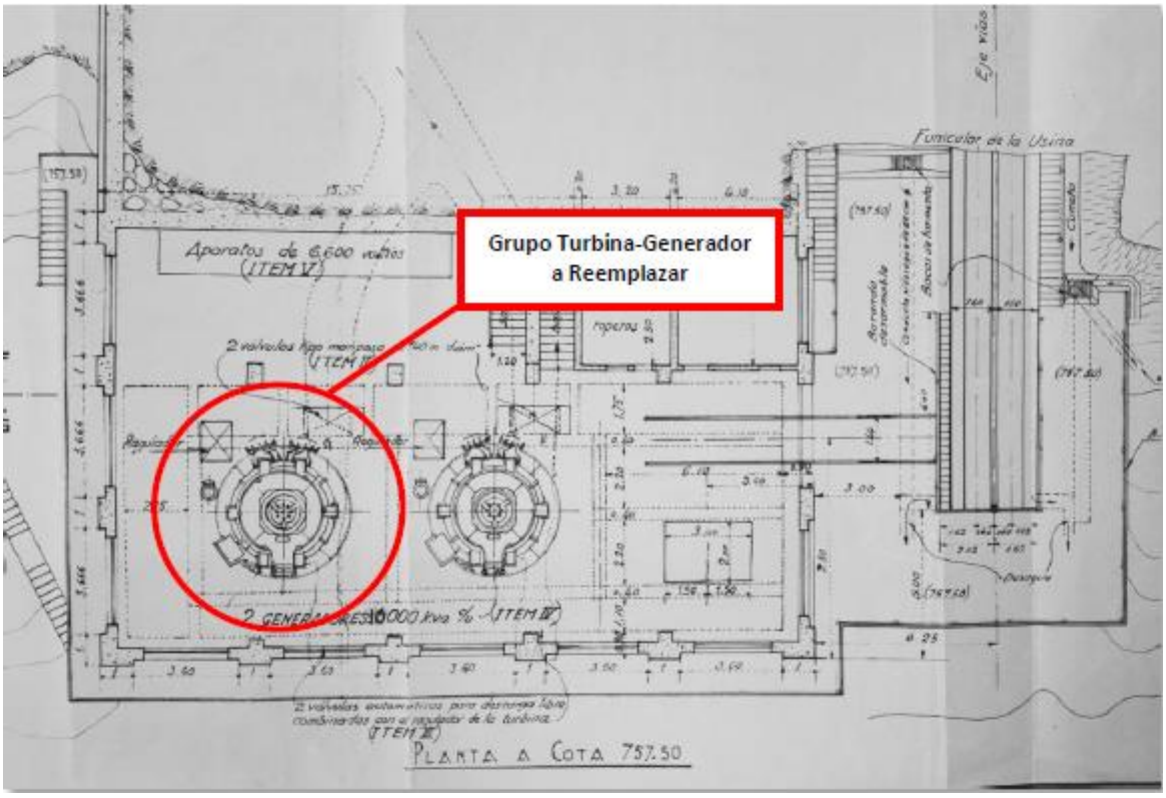

Figura 17: Plano en planta de la central La Viña (se indica el grupo turbina-generador N°2 a reemplazar por una potencia menor, de 6 MW)

Este esquema permitiría:

- Aumentar la flexibilidad operativa.
- Reducir pérdidas por vertido.
- Mejorar la integración del sistema con energías renovables variables.
- Maximizar el uso de infraestructura existente.

Adicionalmente, se planteó optimizar el riego aguas abajo mediante la implementación de sistemas presurizados o de riego por gravedad por pulsos, con el fin de recuperar el nivel del embalse de diseño y asegurar la disponibilidad de agua para el esquema de bombeo.

V. DISCUSIÓN

Lo valioso de las propuestas de refuncionalización y modernización mencionadas radica en aprovechar la inversión original realizada por la provincia en infraestructura civil (presas, túneles, tuberías forzadas, chimeneas de equilibrio, torres de toma y líneas eléctricas), que representa el mayor costo de cualquier proyecto hidroeléctrico. Aun cuando sería necesario realizar una inversión considerable para adaptar las centrales a este nuevo esquema, el esfuerzo permitiría revalorizar obras ya existentes, incorporando capacidad de almacenamiento energético, un recurso clave en la actualidad.

El análisis evidenció que la refuncionalización de centrales existentes a turbinado/bombeo es técnica y ambientalmente viable en Córdoba, y representa una alternativa costo-efectiva para recuperarlas frente a la construcción de nuevas centrales de almacenamiento. Las ventajas principales se asocian a:

- Reutilización de infraestructura civil existente.
- Reducción de impactos ambientales y sociales que ya han sido compensados en el pasado.
- Sinergia con procesos de modernización de centrales hidroeléctricas en curso.
- Incremento de la seguridad y flexibilidad del sistema eléctrico provincial, permitiendo la penetración segura de las energías renovables.

El caso La Viña, actualmente en modernización, constituye una oportunidad inmediata para validar la tecnología a escala piloto y replicarla en otras cuencas.

VI. CONCLUSIONES

La metodología propuesta permitió identificar, con criterios técnicos y ambientales integrados, las centrales hidroeléctricas con mayor potencial de refuncionalización en Córdoba. Según estos criterios, Fitz Simon, Cassaffousth, Los Molinos I y La Viña presentan condiciones estructurales e hidráulicas favorables para su adaptación a turbinado-bombeo. Particularmente, la central La Viña, por su proceso de modernización y disponibilidad de infraestructura, constituye el caso más factible para implementación piloto.

La refuncionalización de las centrales cordobesas a sistemas reversibles puede mejorar el factor de carga, optimizar la gestión del recurso hídrico y aumentar la participación de renovables en la matriz provincial. Se recomienda avanzar hacia estudios de factibilidad técnico-económica detallados para cada sitio y promover un marco regulatorio provincial que incentive proyectos de almacenamiento hidroeléctrico.

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CNT's based Nanomaterials: An Interesting Cluster of Biosensors

Irshad Ahmad & Weqar Ahmad Siddiqui

Jamia Millia Islamia University

ABSTRACT

This article outlines the function of carbon nanotubes (CNTs) in the fabrication of biosensors for various applications. We explain why CNTs are employed more frequently in biosensor fabrications for different applications and why CNTs have significant potential in these areas of application by examining the differences between other members of the nano-carbon family. Furthermore, we investigated the role of these nano-carbons in the detection of different analytes in bio-sensing. This chapter focuses on recent breakthroughs in the construction of sensors and biosensors using carbon nanotubes (CNTs). Biosensors are employed in a wide range of applications, from prosthetic devices to checking food quality. Because of the unique physical features of CNTs nanomaterials for biosensing applications, including optical, structural, mechanical, and thermal capabilities, the scientific community has put in a lot of effort.

Keywords: Carbon nanotubes (CNTs), Functionalization of CNTs, Chirality, Arc discharge, laser ablation, Biosensors.

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Irshad Ahmad[α] & Weqar Ahmad Siddiqui [σ]

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Author α σ: Department of Applied Science & Humanities, Faculty of Engineering & Technology, Jamia Millia Islamia University, New Delhi -110025, India.

σ: Department of Chemistry, C.M. Science College, LNMU, Darbhana-846004, Bihar, India.

I. INTRODUCTION

Biomolecular detection is vital in a variety of critical sectors, including health medications, clinical and infectious pharmaceuticals, food safety, homeland security, and pollution monitoring, as well as illness detection and identification and the recognition and viewing of novel drug molecules [1,2]. As a result, the development of dependable and affordable high-precision/selective technologies that enable direct and quick analysis of biomolecules in the detection of biomolecules can have an impact on human health, allowing for a healthier and more reliable existence [3]. The development and translation of innovative carbon nanomaterials are required for advancements in the field of biosensors [4]. The current COVID-19 epidemic has pushed the quest for novel biosensor materials [5]. The purpose of this paper is to look at biosensors that comprise carbon-based nanomaterials as well as their analytical figures of merit [6]. Biosensors have emerged as a viable choice for medical and biological investigation in applications such as environmental, medicinal, food security, and agricultural [7,8].

The utilization of carbon nanotubes (CNTs) and fullerenes in the construction of novel biosensors has recently piqued interest in carbon nanomaterials research [9]. The inclusion of sensor components permits the production of reliable, precise, and rapid biosensors due to the better capabilities of CNTs. Because of their outstanding properties in the scientific world, carbon nanotubes have spawned a plethora of studies and crucial applications. Chemical sensors, field emission materials, catalyst carriers, electronics, contemporary healthcare applications, and energy storage applications are all possible uses for CNTs [10]. CNTs have several features that make them ideal for chemical and biological sensing because of their unique structure and nanoscale size. Electrochemical sensors for food safety, optical sensors for heavy metal detection, and field-effect devices for virus detection are just a few of the uses for carbon nanotube-based sensors [11]. Large surface area to volume ratios and aspect ratios, strong electrical conductivities, greater chemical stability, and luminous characteristics are among these qualities [12]. CNTs must be purified and functionalized with bio-recognition components to make use of this nanomaterial's unique capabilities in biosensor fabrication. CNTs must be purified and functionalized with biorecognition components to make use of this nanomaterial's unique capabilities in biosensor fabrication [13]. The bio-sensing interface's design is the most difficult aspect of biosensor development. It must take into account both the functionalization and transduction processes. Food safety, health monitoring, counter-terrorism, and virus detection are all possible uses for CNT-based sensors. Even though carbon nanotubes have been reported [14,15] for three decades, few examples of CNT-based sensors have reached the market. Figure 1 shows the CNTs nanomaterials based on various types of biosensors [Ref].

The biomedical application range of CNTs is very broad [16]. There are still obstacles to the widespread use of CNT-based sensors in the real world [17], especially related to the integration of CNT sensing elements into analytical instruments and industrial manufacture. In pristine form it is like wrapped sheet of graphene and generally not solvable in most of the solvent. In some solvable solvent, it forms some bundled structure. It produces bit limitations over its usage.

CNTs' chirality can affect their electrical characteristics, and controlling this chirality can be challenging [18]. CNTs and CNT-based devices face challenges of uniformity and repeatability as a result of this. Small impurities or flaws can substantially alter the characteristics of CNTs, therefore yields and purity are also crucial, and however, these difficulties will influence SWCNTs more than MWCNTs [19]. CNTs must be synthesized with dependable control of physical and electrical characteristics in a highly repeatable way to be feasible for scale manufacturing of analytical devices [20]. Purification and subsequent functionalization of the product are required in all of the major synthesis processes.

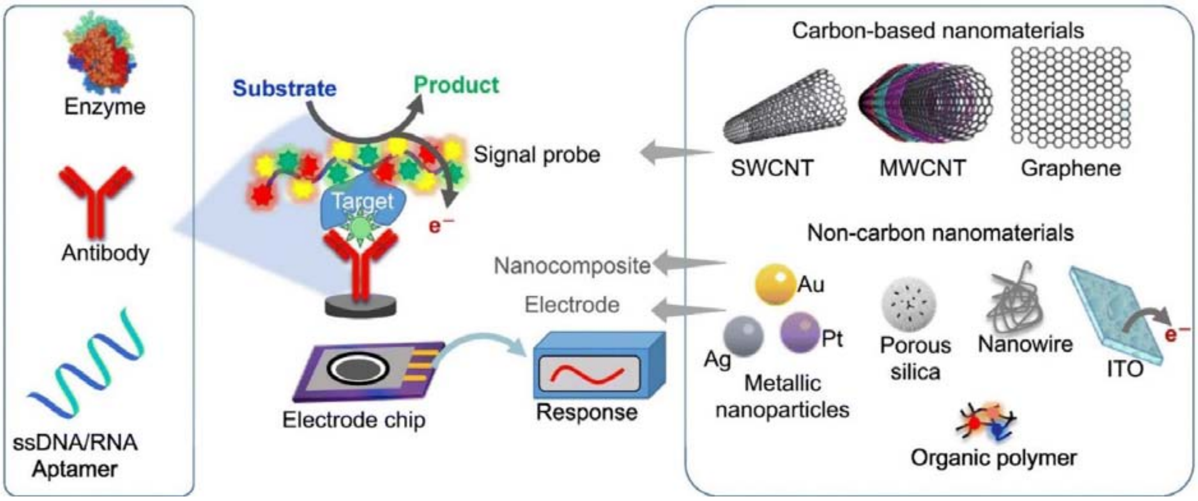

Figure 1: Schematic illustration of the CNTs nanomaterials based biosensor. This figure has been adapted/ reproduced from ref. 83 with permission from Springer, copyright 2020

Carbon nanotubes (CNTs) are hollow carbon structures having one or more walls, a nanometer-scale diameter, and a comparably longer length. They have a well-ordered arrangement of carbon atoms connected by sp_2 bonds, making them the stiffest and strongest fibers yet discovered [21]. Their advantage over other nanomaterials comes from a unique mix of electrical, magnetic, optical, mechanical, and chemical characteristics, all of which hold tremendous potential for a variety of applications, including biosensing [22]. Functionalized carbon nanotubes can infiltrate individual cells and cross biological barriers such as cell membranes. This property, as well as the method by which CNTs are internalized and released from cells, is of great interest for biological and, in particular, intracellular biosensing applications [23].

II. STRUCTURE OF CARBON NANOTUBES (CNTS)

In 1991, Iijima [24] published the first report on multi-walled carbon nanotubes (MWCNTs) and their synthesis, based on findings from an arc evaporation process for the nanotubes determines the diameter of an MWCNT. CNTs are classified into two categories, SWCNTs and MWCNTs each of which is characterized by a distinct model in which Separate sheets of graphene manufacture of C60 fullerenes [ref.19]. CNTs are cylindrical in shape and have nanometer-scale diameters and micrometer-scale lengths. CNTs can be compared to a rolled-up sheet of graphene in terms of structure. Single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) are the two primary forms of carbon nanotubes (CNTs). The numbers of concentric are stacked in concentric cylinders, one within the other, in the Russian Doll paradigm. In the Parchment model, a single sheet of graphene is rolled around itself in the same way as a parchment scroll or roulade cake is wound around itself as shown in figure 2.

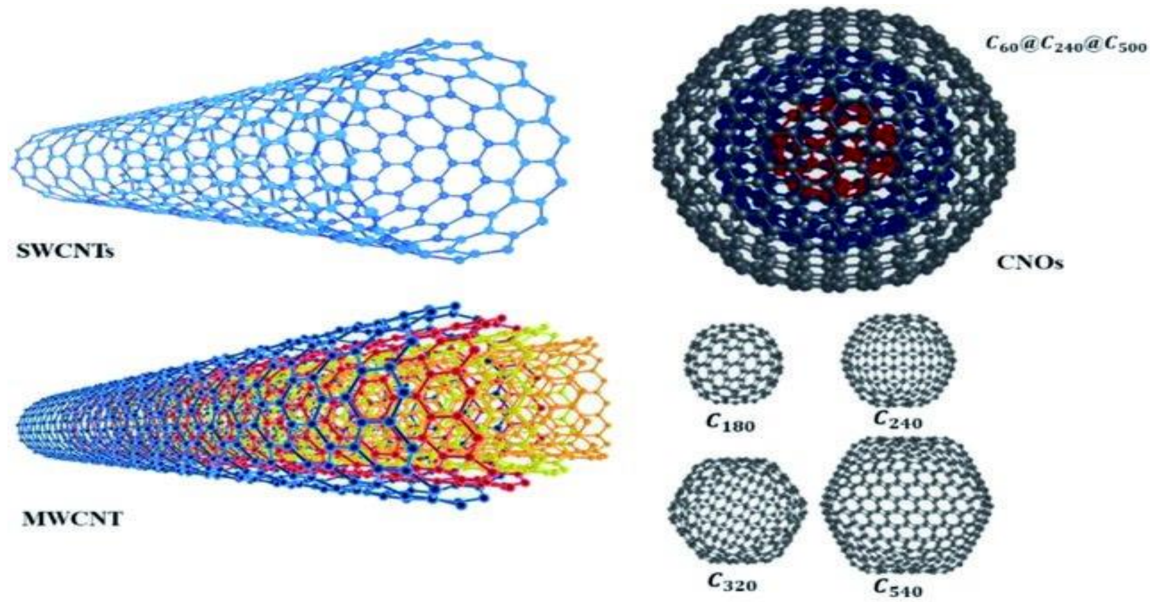

Figure 2: Nanostructures of SWCNTs and MWCNTs, fullerenes and a carbon nano-onion (CNO). Reproduced with permission from ref. 60, copyright 2008, RSC

Multiple-walled carbon nanotubes (MWCNTs) are a particular class of carbon nanotubes with shapes and characteristics comparable to SWCNTs. They are also more chemically stable, making them more resistant to the rather severe chemical procedures required for functionalization [1] diameter of less than 2 nm in most cases. SWCNTs are sometimes referred to as a single big molecule, whereas MWCNTs are a mesoscale graphite system with diameters ranging from 2 to 200 nm.

The geometrical structure and C–C bonding of SWCNTs are responsible for their outstanding mechanical capabilities. One of the strongest bonds in nature is the carbon-carbon bond in graphite's base plane. The Young modulus and tensile strength of SWCNTs with tiny diameters are both high. This suggests SWCNTs are overly stiff and difficult to bend. SWCNTs are, in fact, quite adaptable. The sidewalls of these tubes are form of a hexagonal lattice of carbon atoms, comparable to the atomic planes of graphene, and one-half of a fullerene-like molecule is normally capped at both ends. SWNTs have the simplest form and may be seen as a single graphene sheet wrapped up in a numerous directions that shown in figure 3. The structure of a nanotube may be simply characterized by its chiral vector, which is determined by the chiral indices and is based on the orientation of the tube axis about the hexagonal lattice (n,m). The geometric arrangement of carbon atoms at the cylinder seams is used to classify SWNTs. While the majority of SWNTs are chiral (m 6= n), a few have armchair (m = n) or zigzag (m = 0) layouts. They are flexible enough to be bent like a pipette without breaking. SWCNTs can show metallic or semiconductor behavior depending on their diameters and the chiral angle between hexagons and the tube axis, but MWCNTs can transport up to 10^9 A cm2, are always metallic, and have no bandwidth.

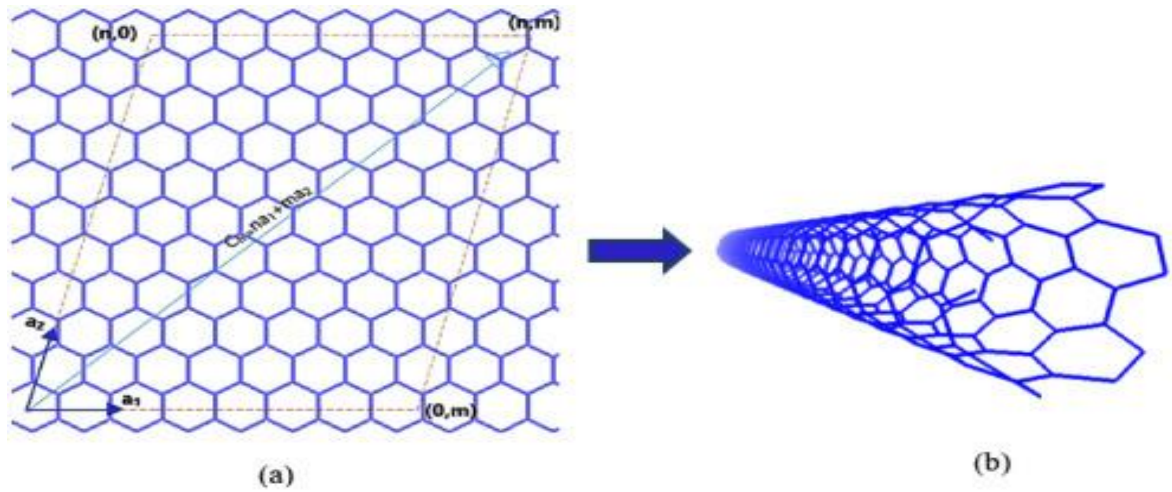

Figure 3: Rolling a graphene sheet in multiple directions to generate an SWCNT is a creative process [Ref]

CNTs are the ideal choice for enhancing bio-sensing instruments because of their exceptional properties, particularly their outstanding electrical properties such as electron mobility (100,000 cm2/Vs), and field-effect mobility (79,000 cm2/Vs), and electrical conductivity (104 S/cm).

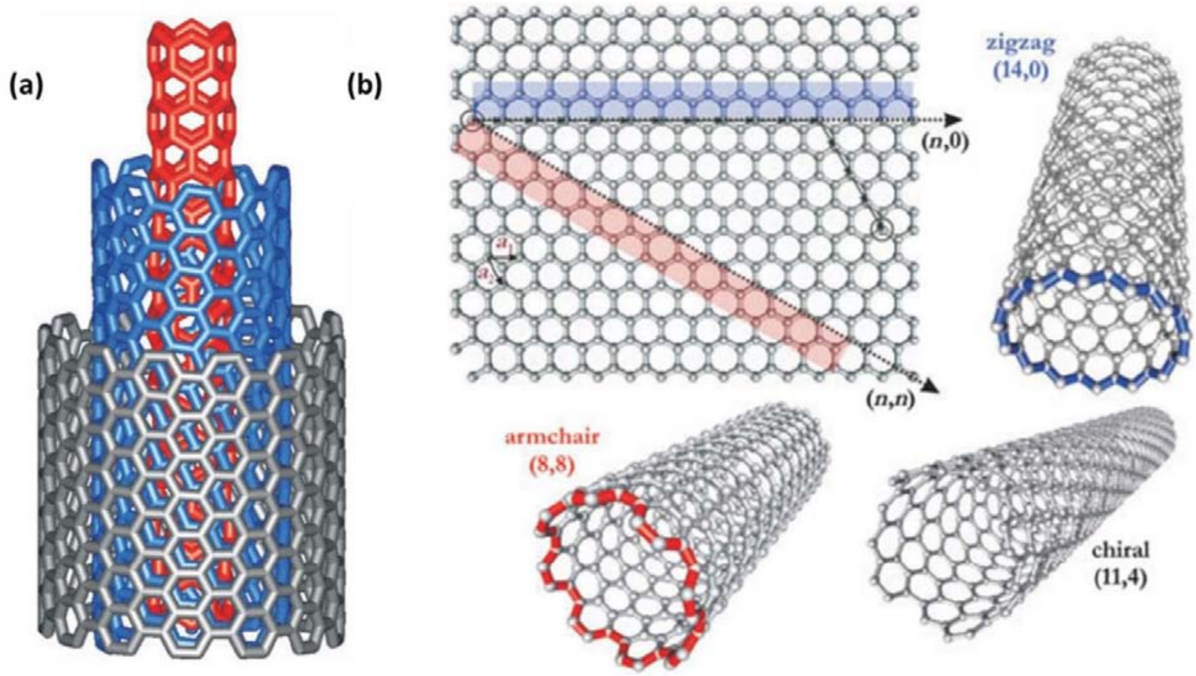

Figure 4: (a) A multi-walled carbon nanotube structure composed of three shells of varying chirality. (b) A graphene sheet is rolled up, resulting in three distinct forms of CNTs. Reproduced with permission from [25]. Copyright (2004) John Wiley and Sons

2.1 Functionalization of Carbon Nanotubes (CNTs)

CNTs have a number-severing qualities and benefits, however, dispersion caused by the CNTs' high surface energy acts as a road-block to future advancement [25]. Because carbon nanotubes have a high hydrophobicity, they are insoluble in water and other common solvents. As a result, CNTs must be functionalized depending on the application to increase their solubility and other functional qualities. The functionalization of carbon nanotubes has become a need for the easy production of nano-devices. Non-covalent and covalent surface modifications are two of the most popular types of functionalization. The fundamental benefit molecules stay unchanged, making subsequent modification exceedingly difficult. CNTs' solubility and compatibility can be considerably altered by direct covalent functionalization. The functionalization of carbon nanotubes has sparked a lot of attention since their carbon chemistry allows for a wide range of changes. Minimizing aggregation, enhancing their water solubility, and improving their biocompatibility have all been investigated. Because carbon nanotubes have a vast surface area, they can accommodate a large number of functional groups. Chemical, physical, and electrochemical procedures are the most prevalent methods for functionalizing carbon nanotubes. Biosensors are being developed by these functionalizing carbon nanotubes [26].

2.1.1 Chemical Functionalization

The chemical functionalization of CNTs is still problematic due to the difficulties in carboxyl, acyl, and hydroxyl groups are the most widely described. This procedure, which is usually reproducibly generating a well-ordered molecular architecture of the electrode surface under mild experimental conditions. A variety of techniques have been developed to change and improve the functioning of carbon nanotubes. The application of acid-based oxidization for the introduction of oxygen-containing combinations is successful in enhancing oxygen-containing functional groups on both functional groups such as carried out using nitric or nitric/sulphuric acid the ends and sidewalls of CNTs. Oxidative therapy, on the other hand, might have a wide range of results. Even though oxidative treatment increases the hydrophilic character of CNTs, controlling the degradation of the electrical, optical, and electrochemical characteristics of CNTs is typically challenging. Defect sites can be introduced during oxidative treatment, resulting in undesirable chemical and physical characteristics. The inclusion of these oxygen-containing functional groups enables the CNTs to be further modified. These can be used as a starting point for adding or converting a new functional group. Strong acid treatments utilized in chemical methods for CNT alterations were shown to be successful not only in adding oxygen-containing functional groups but also in removing metallic catalysts. However, the time required for acid oxidation of CNTs is restricted, and this is frequently deemed undesirable in industrial applications [27].

2.1.2 Physical Functionalization

By adding oxygen-containing groups on the end and sidewall of CNTs, several methods for functionalizing them have been investigated. Plasma treatment has been used to graft various functional groups such as carboxylic, hydroxyl, or amine groups among these methods. A variety of plasma gases, including oxygen, air, a hydrogen-nitrogen combination, or carbon dioxide, might be utilized for this purpose. Plasma techniques are an efficient means of improving the hydrophilic character of CNTs, making biosensor construction easier by allowing biorecognition components to be immobilized. In the case of an aligned configuration of CNTs, microwave plasma treatment with carbon dioxide or nitrogen/hydrogen not only allowed the CNTs to be functionalized but also prevented aggregation, preserving the electrode surface's alignment structure. When compared to the traditional oxidative treatment in a solution, the atmospheric plasma treatment was shown to be more suited for the functionalization of CNTs with an aligned configuration [28-29].

2.1.3 Electrochemical Functionalization

Functionalized CNTs might be functionalized using electrochemistry under mild reaction conditions, avoiding unwanted and uncontrolled reactions. Diazonium salt reactions are a novel way to functionalize the end-tip and sidewall of carbon nanotubes. For function-arising CNTs, interesting findings have been obtained with diazonium salts; nevertheless, due to the spontaneous polymerization process of radical species created by decomposing diazonium salts, getting monolayers with a well-controlled architecture remains hard. CNTs can be anchored to an electrode surface using the diazonium salt technique. It was shown that a well-organized assembly of CNTs may be achieved, resulting in a straight forward method for changing electrode surfaces using CNTs. Aryl diazonium salt derivatives have the benefit of being able to be applied to a variety of surfaces, including CNTs with metal nanoparticles [30].

2.2 Methods for Preparation of CNTs

The use of CTNs in biosensors is becoming increasingly common. As a result, the industry's need for CNT has grown increasingly critical. Arc discharge, laser ablation, and chemical vapor deposition are some of the synthesis methods used.

2.2.1 Arc Discharge

The arc discharge is one of the most used ways of preparing carbon nanotubes, and it was initially used to generate CNTs by Iijima in 1991 [31]. The idea of this approach is that CNTs are deposited on the graphite cathode in a vacuum reactor under the action of the current. The cathode is a bulky graphite rod, whereas the anode is a fine graphite rod; the spacing between the two graphite electrodes has remained within 1 mm, and the arc has remained stable. To prevent CNT oxidation, the vacuum reactor is filled with a specified amount of inert gas, such as helium or argon. CNTs are frequently synthesized under certain loading conditions, such as high current (50-120 A), high voltage (20-30 V), high temperature (>3000 °C), and low pressure (50-700 bar). The graphite and metal catalyst of the anode graphite rod is vaporized and consumed continuously during the arc discharge process under a high-temperature plasma; CNTs are deposited on the graphite cathode following the action of metal catalysts. The synthesis of CNTs is dependent on the selection and management of process parameters such as arc voltage, current, inert gas pressure, and electrode cooling speed. The selection of metal catalysts for CNT synthesis is equally critical since it affects the preparation's efficiency. The arc discharge is one of the most well-established synthetic processes for SWCNTs, and it is also one of the most widely employed. Varied catalysts for the production of SWCNTs result in different diameter distributions, according to research [32].

2.2.2 Laser Ablation

Smalley and his colleagues developed laser ablation as a simple and effective new technology based on arc discharge. To begin, a piece of graphite is put in a vacuum furnace filled with an inert gas (for example, helium) and heated to a high temperature. The high temperature will be created quickly utilizing a high-energy laser beam to irradiate the metal catalyst and carbon atoms of targeted graphite, prompting them to evaporate, and then the carrier gas will transport these carbon molecules and catalyst particles to the high-temperature zone. To make CNTs, the carbon atom clusters are finally placed on the collector. The most notable benefit of laser ablation is the excellent purity and low defect rate of the CNTs generated. Furthermore, the yield of CNTs might be as high as 70% to 90%. However, because this technique of growing CNTs has a high initial investment cost and significant energy consumption, it is challenging to use in commercial manufacturing [17,33].

2.2.3 Chemical Vapor Deposition (CVD)

CVD is a thermal dehydrogenation reaction that requires a transition metal catalyst, and it is one of the most extensively used and well-explored methods for the synthesis of CNTs. First, the carbon source gas and carrier gas enter the reaction chamber at a temperature of 600–1000 °C, where the gas is decomposed to form carbon atoms on a coated catalyst substrate at a high temperature, and eventually, CNTs are produced. Co, Fe, Ni, Cu, Cr, Mo, and their alloys are often used as transition metal catalysts. Carbon gases such as methane, ethanol, ethylene, acetylene, and benzene are commonly used as carbon sources. This may aid in lowering the temperature necessary for gaseous hydrocarbon breakdown into carbon and hydrogen. Carbon supply, gas flux, carrier gas flux, growth temperature, and catalyst concentration are the most important CVD process factors. CVD is split into the matrix technique and floating catalyst method based on the loading and dispersion methods of the catalyst. CVD has the benefit that CNTs can grow directly on the substrate, and the equipment is simple and inexpensive. It is worth mentioning that this technology may be used for mass manufacturing indefinitely [34].

2.3 Different CNT-based Biosensor's Working Principles

Clark's 1962 description of the enzyme electrode inspired the notion of a CNT-based biosensor; CNT-based biosensors are made up of two parts: a biologically sensitive element and a transducer. The biological sensitive element is a CNT functionalized with biomolecules or receptors, such as proteins, oligo- or polynucleotides, microbes, or even complete biological tissues. For testing and detection, the transducer converts analyte concentrations to other observable physical signals such as currents, absorbance, mass, or acoustic variables. CNT-based biosensors will be divided into two groups depending on the interactions between analytes and biologically sensitive materials, which will be explored in the following sections: chemical and physical. The CNTs-field transistors, which have better characteristics, will be emphasized after this section [13, 35].

2.4 Biosensors based on Carbon Nanotubes

The first biosensor was produced in 1906, but Clark et al. invented the real biosensor in 1956 and became the father of biosensors. He then created an amperometric enzyme electrode for glucose sensing in 1962. Based on the interactions between the analytes and the biological sensitive materials, CNT-based biosensors were divided into two categories (chemical and physical).

2.4.1 Electrochemical CNT Biosensors

Various signal amplification methodologies using CNTs have been explored to develop ultrahigh sensitivity biosensors. Because of the reactive assemblies on the outer surface of CNTs, they have fascinating electrochemical characteristics. CNTs have been hailed as a promising material for electrochemical biosensors because of their ability to improve electron transfer. Electrochemical biosensors function on the premise of converting/transferring a biological event into an electrochemical signal using a two or three-electrode electrochemical cell (reference, working, and counter electrode). High sensitivity, cheap production cost, rapid response, ease of operation, and prospective mobility distinguish CNT-based electrochemical biosensors as outstanding materials in biomedical applications [36].

2.4.2 Electrochemical Enzyme Sensors

Since the creation of the first enzyme-based biosensor for the detection of blood glucose, electrochemical biosensor technology, and research have evolved tremendously. Enzyme-based electrochemical biosensors are a subclass of chemical sensors that combine enzyme specificity and selectivity with electrochemical sensing's high sensitivity. The common enzymes used in biosensor development of oxidoreductases, catalyze oxidation-reduction events involving the production of electro-active substances. One of the most difficult aspects of designing enzyme-based electrochemical biosensors has been achieving effective electrical communication between immobilized enzymes and the electrode surface. The benefit of this generation is that the concentration of diffusive electroactive species and the measured current are directly proportional. Biosensors that do not require the use of a mediator are referred to as mediator's biosensors. Electrochemical biosensors based on enzymes are a type of chemical sensor that combines the specificity and selectivity of enzymes with the high sensitivity of electrochemical sensors. Several studies using enzymes such as glucose oxidase horseradish peroxidase, lactate oxide, and malate dehydrogenase have been published. Oxidoreductase-based electrochemical biosensors including oxidoreductases are enzymes that catalyze oxidation/reduction reactions by making electron transfer from reductants (electron donors) to oxidants easier (electron acceptors). Electrons are eventually transferred to convert ADP to ATP in most oxidation processes. Non-protein chemical substances or metallic ions that are essential for enzyme action are known as cofactors. Coenzymes are complex organic cofactors. Several coenzymes have been found, and vitamins are the most common cofactors. $X^- + Y \rightarrow X + Y^-$. Where, X is the reductant and Y is the oxidant, is the typical reaction. They work with inorganic and organic cofactors to act on diverse functional groups like --CHO, -CHOH, CH2-NH2, -CH=NH, or -CH2-CH2-. Electron transfer reactions between biomolecules catalyzed by oxidoreductase (especially NAD(P)H) play critical roles in the metabolism and catalysis conversion of various materials in plants and liver tissues, including adenosine diphosphate (ADP) to ATP cycles, ethanol to acetaldehyde, glucose to gluconolactone, pyruvate to lactate, and so on. Furthermore, NAD(P)H's reducing capacity is necessary for additional metabolic pathways that are catalyzed by various enzyme and coenzyme cofactors [37].

2.4.3 Electrochemical Immunosensors

Immunosensors are condensed analytical biosensor devices based on ligand affinity, in which immunochemical reaction interaction and molecular recognition between antigen and antibodies are connected to a transducer for selective detection of various proteins. Immunosensors are devices that make use of antibody-antigen binding interactions. A sensor surface can be immobilized with either the antibody or the matching antigen, and the binding of the corresponding member of the pair, producing a stable complex, can be detected using several methods. By combining SWCNT forests with enzymes and horseradish peroxidase, the electrochemical immunosensor displayed extremely low and enhanced cancer-related detection of interleukin-6, a multifunctional cytokine. Because of the very particular nature of their bonding with their respective antigens, antibodies are commonly utilized in biosensing applications, and there are several instances of CNT-immunosensors [38].

Furthermore, MWCNTs-based impedimetric immunosensors adorned with gold nanoparticles have been effectively used to detect cancer cells in serum, particularly in breast cancer patients. The combination of highly conductive ionic liquid and MWCNTs, as well as gold nanoparticles, improved the sensitivity of the proposed immunosensor while also improving biocompatibility and amplification power [39].

2.4.4 Electrochemical DNA Sensors

Because of its powerful and very specific hybridization, DNA is an appealing bio-recognition component for sensors. Medicine and healthcare, food safety, and counterterrorism are just a few of the applications that DNA sensors might be used for. Covalent binding of the nucleic acids' amine terminal to CNT-functionalized electrodes is a typical way of immobilizing nucleic acids onto CNT-functionalized electrodes.

The sensing element of a DNA biosensor is a nucleic acid, such as single-stranded DNA (ssDNA) or double-stranded DNA (dsDNA). It has been discovered that ssDNAs adsorb strongly on CNTs, but duplex DNAs are unable to attach to CNTs in a stable manner. This one-of-a-kind characteristic has been used to meticulously build CNT-DNA biocomplexes for use in biosensing technologies for a variety of molecular targets. The SWCNT serves as a transducer, converting and amplifying DNA hybridization on Au into an electrical signal that can be measured immediately. This newly created sensing platform has proved to have considerably simpler chemistry and setup than most currently available optical and other electrochemical DNA biosensors. Furthermore, a simple and ultra-sensitive DNA biosensor based on MWCNT signal amplification and fluorescence polarization (FP) detection for monitoring the activity and inhibition of DNA methyltransferase (MTase) in a homogenous solution has been successfully created. DsDNA and restriction endonuclease was used to make the DNA probe. Restriction endonuclease without DNA MTase cleaves the FAM-labeled DNA probe [40].

2.4.5 Non-Biomolecule-based Electroche-mical Sensors

Sensors based on molecularly imprinted polymers have gained popularity in recent years (MIPs). MIPs are antibodies that have been synthesized. Simply said, polymers are made with the target molecule attached to the polymer structure either covalently or noncovalently. While the biomolecule-based sensors discussed in the preceding sections are likely the most popular electrochemical CNT-based sensors, there are numerous more that do not use biomolecules as recognition components. CNTs are of particular importance for MIP applications because they may increase the porosity and mechanical characteristics of polymer composites while also imparting or enhancing electrical conductivity. CNTs have also been widely employed to functionalize electrode surfaces to increase the sensitivity of direct electrochemical detection for a range of analytes in combination with other nanomaterials. Noble metal nanoparticles, such as gold and silver, have been utilized to functionalize electrodes for the detection of analytes such as glucose, urea, bisphenol A, and volatile organic compounds (VoCs) alongside CNTs [41].

2.4.6 Optical Biosensors

The CNTs have shown great optical behavior and the feature of showing different kind of luminescent behavior makes them an ideal optical probe for biosensing. They have shown photoluminescence, fluorescence, electroluminescence, cathodoluminescence, Raman scattering etc. The CNT's can play very important role in the fabrication of variety of optical biosensors. Specifically, the single walled carbon nanotubes [SWCNTs] are very promising one for the purpose. CNTs' luminous features may be used for biosensing applications using a range of biomolecules. Optical biosensors work on the premise of sensing photons (absorbance, reflectance, or fluorescence emissions) rather than electrons to detect and analyze interactions between target biomolecules and analytes. Optical transduction methods are extensively utilized in biosensors because they have excellent sensitivity, stability, and multiplex detection capabilities. CNTs are commonly used in fluorescence sensors and biosensors because their fluorescent characteristics are strongly reliant on their physical structure. CNTs can also be used to quench fluorescent light. Fluorophores can be used to mark bio-recognition elements like oligonucleotides. The oligonucleotides are then non-covalently linked to CNTs, quenching the fluorophores. Surface plasmon resonance (SPR) is a very sensitive optical method that is frequently used in chemical and biological detection. It uses optical stimulation to induce the creation of surface plasmon waves at the interface between metal surfaces, such as gold, and a dielectric. The fact that SWCNTs emit light between 700 and 1400 nm qualifies them as biocompatible fluorescence probes. SWCNTs have a wavelength range that permits rays to penetrate deeply through layers of skin, allowing in vivo imaging of biological tissues and organs with a dosage limit that is nearly 15 times lower. SWCNTs have also been used as NIR fluorescent markers for precise cell probing and imaging. The fluorescent characteristics of carbon nanotubes have also been used to detect COVID-19. A simple and quick fluorescent sensor for the SARS-CoV-2 spike protein was demonstrated by non-covalently binding the protein ACE2, which has a high binding affinity for the SARS-CoV-2 spike protein [42].

2.4.7 Cnts as a Field-Effect Transistor Biosensors

Field-effect transistors (FETs) are three-channel devices with source (S), drain (D), and gate (G) electrodes that are often employed to amplify weak signals. The voltage generated in the device is controlled by the gate electrode. Because silicon-based transistors have hit their scaling limit, CNT-based transistors are currently seen as one of the most promising possibilities to replace existing silicon FETs. With an increase in current density, the device transistor footprint encompassing all components (S, D, and G) can be lowered to less than 40nm during the next decade. As we all know, the existence of high hysteresis in CNTs degrades their performance as a transistor, which is a key downside as an energy-efficient material. To lower conductivity, the first biosensor-based SWNTs were bound with the enzyme GOx. However, when dissolved in glucose, these semiconducting SWNTs serve as reversible pH sensors, implying that they may be used as an enzymatic biosensor. The FET biosensors based on N-acetyl-D-glucosamine (GlcNAc)-fSWCNTs controlled secretion (or exocytosis) of PC12 cells in real-time detection. Because CNTs have a high conductance, these networking molecules can make them more sensitive to the electrochemical concentration at the surface [43-45].

III. FUTURE PROSPECTIVE

The physical and electrical features of CNTs have been highlighted in the preceding sections as being excellent for the construction of biosensors. To improve or exploit these properties, CNTs may be mixed with a variety of different nanomaterials to make composite materials. Food safety, health monitoring, counterterrorism, and virus detection are all possible uses for CNT-based sensors. Even though carbon nanotubes have been around for three decades, few CNT-based sensors have made it to market. There are still obstacles to the widespread use of CNT-based sensors in the real world, especially related to the integration of CNT sensing elements into analytical instruments and industrial manufacture. As the world's health systems respond to the effect of the coronavirus pandemic in the early 2020s, research interest in quick viral diagnostic techniques, as well as areas like point-of-care patient monitoring, will likely increase. CNTs have attracted a lot of attention in biomedical engineering during the last decade because of their diverse surface characteristics, size, and form. CNTs are becoming a promising material due to their inorganic semiconducting capabilities as well as their organic–stacking features. As a result, it could successfully interact with biomolecules while also responding to the light. CNT-based nanomaterials might be utilized to produce biomedical applications in the future by combining these features into a single entity. CNT-based analytical devices will undoubtedly play a prominent part in many of the approaches to these difficulties because of their potential for building biosensors with high sensitivity and quick reaction times.

IV. CONCLUSION

CNTs' exceptional electrochemical characteristics have cleared the way for their usage as platforms for the development of a wide range of electrochemical biosensors with better analytical performance. In vivo detection with reduced cytotoxicity, high sensitivity, and long-term stability is possible using CNT-based bio-sensing for reliable point-of-care diagnostics under physiological settings. Furthermore, these applications are not limited to the medical area, but also have a wide range of uses in the food, water purification, and agricultural industries, among others. As a result, it's safe to state that CNTs' genuine bio-sensing applications are still a ways off. Although CNT-based biosensors appear promising, there are still several practical problems in terms of implementation. Biosensor manufacture, for example, often requires a precise size and helicity, but controlling the size of CNTs during production is difficult. It's also difficult to mass-produce CNTs in a cost-effective and high-purity manner, which is why the present market price of CNTs is far too exorbitant for any practical commercial application.

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Development of Nanotechnology for Manned and Unmanned Aircraft: Perspectives on Jet Engines, Fuels, Spacecraft, AI, and Sustainability

Yusuf Karimli & Thomas J. Webster

Brown University

ABSTRACT

These days, nanotechnology has provided an enormous benefit to the aviation and aerospace industries for improved manufacturing, spacecraft, fuels, health, and more. The objective of this paper is to review and propose a higher level of nanotechnology development in the aviation industry. While space exploration and tourism have sparked an appreciation for Earth's environmental changes from space, numerous criticisms have highlighted the significant negative impact space travel has made on the environment. Here, nanotechnology is presented as a field that can both enhance space tourism and mitigate its environmental impact on the Earth. Specifically, this paper starts with a review of what material properties are needed for space exploration and suggests the use of nanotechnology in the development of improved composite materials for jet engines, propulsion, and durability, considering aeronautical standards and aerospace developments, and introducing the implementation of artificial intelligence (AI). This research includes aerospace and aeronautical industry manufacturers, their new nanotechnological strategies and breakthroughs, as well as failed attempts during manufacturing or operations.

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Author α: LANDAU School, Baku, Azerbaijan.
σ: Brown University, Division of Pre-College and Undergraduate Studies, Providence, USA.

I. THE MOST EFFICIENT, FASTEST, AND IDEAL TRANSPORTATION OF HUMANS OR GOODS AROUND THE GLOBE:

The most efficient, fastest, and ideal transportation of humans or goods around the globe is when using aircraft, which are operated by ideal engines. Similarly, current technologies provide spacecraft with thrusters to enable transportation to space; however, such approaches can significantly harm the environment. For instance, aircraft emitted approximately 1000Mt CO_2 per year in 2023 and are estimated to emit more according to future global development, as seen in Graph 1. However, rockets transmit an outsized amount of pollution compared to airplanes, with rockets transmitting ~200-300T of CO_2 per dispatch. As of 2022, NOAA evaluated that rockets radiate ~1,000T of dark carbon into the environment each year (1). In large part, the enormous amount of energy needed to get into the upper atmosphere and/or space lies in the aircraft and spacecraft materials available to us today, which are heavy due to strength, thermal, radiation opacity, and other requirements. New lighter materials meeting such properties would decrease energy needs. In addition to lighter, more energy-efficient materials, the quest for new materials has risen in part because the melting point of superalloys that are already in use is only about 1,850°C. This presents a problem in terms of discovering materials that can tolerate higher temperatures. A probe visiting Jupiter, for example, would require a conductive surface with high heat resistance to ward off electrical jolts from Jovian charged-particle belts. An example of such a superalloy is Dunmore (2). Metals like tungsten, molybdenum, niobium, and tantalum possess high melting points. They are applicable for extreme heat conditions like furnaces, jet engines, and aerospace components (3). A major factor driving demand for these new materials is the introduction of lean-burn engines, which have temperature potentials as high as 2,100°C (4). Further, engines need to be lighter without sacrificing thrust to attain higher efficiency. Higher operating temperatures also need to be simultaneously reached. However, such materials (such as the heavy metals mentioned above) are not environmentally friendly, and in addition population caused by their use, they also present high carbon footprints during manufacturing. New material families that are lighter with higher melting points and higher inherent strengths that don't harm the environment during manufacturing need to be developed.

The above implies that heavy materials can be replaced with light materials or novel surface treatments of light materials to provide optimal properties. For instance, Kernite plasma electrolytic oxidation (PEO) also protects components from their aggressive surroundings. The investigation and inception of how the current materials used in outer space are evolving, and the use of light materials as coatings, is paving the way for more ambitious undertakings (5). The secret to increasing lighter coating alloys may not be new to space, but the innovations that enhance them are becoming ever more capable. Transformation coatings, like PEO, can provide erosion protection, passive thermal control, and reflectivity control needed in space, in addition to: security against cold welding, galling, and physical impacts; great attachment to avoid molecule generation, which can reduce the lifetime of optical assemblies in space; radiation resistance in its many forms, including AO, P+, E-, and optical; resistant to extreme temperatures and thermal shocks; materials with extreme temperature resistance of up to 450 °C and cryogenic temperatures as low as -185 °C; and corrosion resistance during time spent in operation.

The viability of space travel that does not harm the environment may lie in nanotechnology, and more specifically, nanomaterials. Nanotechnology is the use of materials with at least one dimension in the nanometer range. Nanotechnology not only creates improved lightweight and strong materials with more fuel efficiency, better control systems, and automated AI, but it can also create materials able to withstand the high temperatures of aircraft and spacecraft engines. Fundamentally, compared to conventional materials, due to their greater surface area to volume ratio, nanomaterials are stronger, more temperature resistant, more conductive, possess greater radioactivity, are lighter, and more. One of the ideal options for jet engine manufacturing or rocket booster manufacturing is nanotechnology: a promising technology that promotes efficiency, durability, compatibility, and an advanced approach for future aviation and aerospace needs. The objective of this paper is to review what has been accomplished in the search for new materials, specifically nanomaterials, for simultaneously traveling to space without significantly harming the environment in the process.

II. METHODS

2.1 Data Source and Participants

The research was completed for this study by using literature searches on the Web of Science over the past 2 years. The Brown University Pre-College and Undergraduate Program course entitled "Space Tourism" provided crucial additional information to conduct research and develop an analytical understanding of aerospace composites and sustainable engineering, and how nanotechnology can be beneficial. Additionally, this research used the Sustainable Development Goals (SDGs) of the United Nations, specifically addressing all clauses and aerospace nanotechnological advancements and developments according to SDG-9, SDG-12, SDG-13, and SDG-17 which are calling upon all for "Industry, innovations and infrastructure", "Responsible consumption and production", "Climate action" and "Partnerships for the goals" accordingly (19). Lastly, this manuscript references the United Nations Office for Outer Space Affairs (UNOOSA) and over 40 acknowledgments and papers signed for the future development of space affairs (20).

III. RESULTS AND ANALYSIS

3.1 Overall

Results from the study demonstrate that nanomaterials have a strong future outlook for space travel. For example, to reduce the negative impact of aircraft and spacecraft on the environment, jet engines can be made of sustainable, efficient, malleable, and versatile composite materials, as seen in Figure 1. Moreover, there are numerous promising applications of nanomaterials in aircraft and spacecraft, as highlighted in Table 1 and grouped according to their promising properties below.

3.2 Thermal stability

Materials requiring a high degree of wear resistance and thermal stability can be made with silicon carbide (SiC) nanoparticles. Because of these characteristics, nano SiC is a perfect material for parts found in spacecraft high-temperature areas like jet engines, where it helps to sustain performance under harsh circumstances. Boron nitride nanotubes (BNNTs) also stand out for having excellent electrical insulation and thermal stability (8). Their application lies in spaceship thermal protection systems, where they offer superior heat resistance while reentering Earth's atmosphere. In the extreme heat experienced during space missions, this material guarantees the structural integrity of the spaceship. Structural composites of jet engines should also employ carbon nanotubes (CNTs) for their incomparable strength and flexibility, making them the best choice for aircraft frames and jet engine manufacturing (9). Airbus and Boeing implemented CNTs in fuselage composites and wing manufacturing for aircraft to minimize weight, prove the flexibility of the structure, and increase the fuel efficiency of the aircraft. Looking ahead, the proceeded integration of nanotechnology in aviation holds the guarantee of assisting headways in fabric execution, empowering the advancement of lighter, more effective airplanes, and clearing the way for advancements that may revolutionize air travel (10). A large number of nanomaterials, particularly inorganic materials and some organic materials like graphene, have high-temperature resistance, meaning they can survive extremely high temperatures without degrading. These substances add fire-retardant qualities to other substances when they are combined with them, for example, in the various polymers used in aircraft or the textiles used for the upholstery. The addition of nanoparticles to other materials can not only increase their fire resistance but also lessen the number of harmful gases that are emitted if they catch fire. Vibrations that enter an aircraft's cabin can also be reduced by adding nanomaterials to the airframe and other structural parts. This might lessen the outside noise that enters the cabin (11). Nanotechnology improves the aero arena, proving the newest technology for the development of jet engines, and elements such as lithium, Kevlar, carbon, silicon, iron, and aluminum are reinforced to composite nanomaterials for the manufacture of aircraft and spacecraft. For instance, nano lithium batteries are used in the aerospace industry and, despite not being very popular, are an incredible source of sustainable power and energy for spacecraft and aircraft.

3.3 Electrical properties

Additionally, nanomaterials have improved electrical properties. Depending on the kind and quantity of nanoparticles utilized, nanomaterials might give composite electrical conductivity or insulating qualities. This characteristic may be useful for aircraft parts that need electrical features or protection against electromagnetic interference (EMI). As seen in Table 2, we present the temperatures for melting superalloys, a characteristic used as protection from EMI, and we provide several perfect composite materials for space and aircraft manufacturing, such as Nano-Li, nano silicon carbide, nano nickel, nanofibers, and nano titanium, that should be further investigated for this purpose.

3.4 Mechanical properties

Furthermore, some nanomaterials possess the ability to cure or fix themselves mechanically when failing, allowing for matching nanocomposites to self-heal minor damages.

Aerospace structures exposed to hostile environments may have a longer lifespan and be safer because of this trait (12). The casing and fan should be manufactured out of aluminum oxide nanoparticles, the combustion chamber out of nanotechnologically developed tungsten and tantalum/ceramic mixes, the exhaust nozzle and turbine out of nickel nanoparticles, and the compressor out of cobalt/nickel nanoparticles.

Moreover, because nanocomposites can alter surface characteristics and lower drag, their application in the design of aeronautical surfaces can result in enhanced aerodynamics and stealth qualities. Considering lowered drag and air resistance and the result of enhancements in aerodynamics, aircraft require less fuel and can have a higher operational range, allowing the aircraft to operate longer-haul flights, widening the benefits for the airline operator. Also, aircraft have greater endurance and higher speeds due to enhancements. As depicted in Graph 2, nanotechnology has been and should continue to be applied to the transportation industry on the road towards high-energy-density batteries (13).

3.5 Solar Sails

Nanomaterials have advanced to the point that lightweight solar Sails (a method of spacecraft propulsion using radiation pressure exerted by sunlight on large surfaces). Employing carbon nanotubes creates solar sails that are lightweight and drive spaceships by harnessing the pressure of light reflected from the sun onto a solar cell that resembles a mirror. This eliminates the need to launch enough fuel into orbit to sustain spacecraft on interplanetary voyages. These developments could drastically reduce the cost of entering orbit and space travel by lowering the amount of rocket fuel needed. Furthermore, novel materials in conjunction with nano sensors and nanorobots may enhance the functionality of spacecraft, spacesuits, and other tools used for planet and moon exploration. Using carbon nanotube-based composites to minimize weight while maintaining or even improving structural strength in spacecraft is a promising future direction.

3.6 Space Elevators

A space elevator (a proposed type of planet-to-space transportation system) cable is now feasible. In the traditional conception of a space elevator, a cable would be anchored in the ground and reach around 42,000 kilometers (26,098 miles) above Earth, beyond geosynchronous orbit. A cable like that would be quite heavy. It would therefore need to be balanced at the opposite end by a comparable orbital mass to prevent it from falling. Centrifugal forces would subsequently be used to support the elevator. The scale of these forces has long fascinated scientists, science fiction authors, and visionaries, but the results have unfortunately discouraged them. Not even the strongest contemporary carbon fiber polymers, nor spider silk, Kevlar, or any other material, are strong enough to withstand these forces (14).

Constructing the space elevator's required cables out of carbon nanotubes is a method that might significantly lower the cost of lifting cargo into orbit. Including spacesuit layers with bio-nano robots. The outermost layer of bio-nano robots would react to spacesuit damage by sealing holes, for example. In the event of an astronaut emergency, an inner layer of bio-nano robots may react by supplying medication (15). This decreases the thruster system weight and complexity when employed on interplanetary journeys. Rather than designing and fabricating separate engines for different-sized spacecraft, these thrusters can draw on more or less of the Micro-Electromechanical Systems (MEMS) devices, depending on the size and thrust needs of the spacecraft. This feature helps to save costs. Further, by monitoring the performance of the life support systems on board, a spacecraft using nano sensors can track the amounts of trace substances. Given the small size of nanowires, nanoparticles, and nanotubes, it only takes a few gas molecules to alter the electrical characteristics of the sensing elements. This makes it possible to detect chemical vapors at extremely low concentrations. The idea is to have cheap, tiny sensors that can detect chemicals in the same way that dogs are used in airports to detect the smell of drugs or bombs (15). The faster, better, and cheaper space transportation incorporates nanotechnology and depiction of the size of the discussed tiny sensors and nanotubes, as seen in Figure 2.

3.7 Sterility

In spacecraft, sterility is largely attributed to the engine and operating parts of the machine (6). Hence, sterility and durability of the engine are merits of nanotechnology, allowing for the prevention of bacterial growth around the spacecraft and aircraft, which also provides a safe environment for the crew and passengers onboard. Further, many additional nanochemistries can be used in space tourism and space exploration, as seen in Table 3. For example, since silver nanoparticles have strong antibacterial qualities [7], they should be employed as coatings and filters to sanitize craft surfaces, space suits, and air in cramped areas of spaceships and aircraft. Moreover, our research showed that not only can nanomaterials help in space travel based on improved thermal, electrical, mechanical, solar, etc. properties, but those same materials have enhanced biological properties to prevent, diagnose, and treat diseases. Clearly, when one is in space, new materials are not available for treating unexpected health problems, and nanomaterials may then be transferred from other functions to improving health.

Improved properties while reducing harm to the environment: As discussed, the results from the study found that nanomaterials have numerous attractive properties for space travel, including thermal, electrical, mechanical, solar, biological, and more. Impressively, it has been demonstrated that fewer nanomaterials can achieve similar and even better properties than larger-scale conventional materials. This provides for less material usage, manufacturing, and less harm to the environment. Moreover, due to these attractive properties, nanomaterials foster new, less environmentally harmful ways to get into space, such as the aforementioned solar sails and space elevator. Thus, this study found that nanomaterials possess the ability for more efficient space travel with less harm to the environment.

IV. DISCUSSION, LIMITATIONS, AND IMPLICATIONS

4.1 Nanotechnology's Impact on Aerospace Innovation

A business analysis earlier this year estimated the value of the aerospace nanotechnology sector at US$5.6 billion by 2022. The market would develop at a compound annual growth rate (CAGR) of 4.6% and reach US$8.1 billion by 2030, according to the analysis. According to a report by Infinium Global Research, the aerospace nanotechnology market is primarily driven by the growing use of carbon nanotube nanocomposites in the manufacturing of airframes. The strength and durability of a material are increased when carbon nanotubes are reinforced into it (16). NASA spacecraft components and missions like Chandrayaan-3 are utilizing nanotechnology's enormous potential. They are setting the stage for historically significant advancements in space exploration by utilizing nanomaterials and nanoscale sensors. Through these breakthroughs, the space industry is increasing the potential for extraterrestrial exploration while also stretching the bounds of human knowledge (17). Spacecraft components are becoming stronger and lighter because of the usage of nanomaterials like carbon nanotubes, which enable one to build and develop more sophisticated and effective spacecraft. Our comprehension of the universe is improved using nanoscale sensors, which are essential for gathering information and keeping an eye on the space environment. The effects of nanotechnology don't end there. With features like UV protection, self-cleaning capabilities, and ideal thermal management, it has completely changed the space suit industry.

This expansion in materials enabled by nanotechnology indicates the possibility for further breakthroughs in material science, fuel economy, aerospace technology, and overall industry sustainability, in addition to providing economic opportunities. The reduction of the weight of nanomaterials in aerospace causes greater fuel efficiency and lower release of carbon dioxide gas, as well as toxic gases such as methane. Aircraft components can break in high-stress locations due to the varied stresses they experience during flight. A structure may collapse and people may die if structural components are not routinely inspected and fixed. Cracks may also worsen with time. Nevertheless, airlines must pay for the examination and maintenance of aircraft. The necessity for increased fuel efficiency has also been highlighted by rising fuel prices and global climate change initiatives. Rapid, inexpensive manufacturing of dependable, effective, and easily maintained aircraft with greater load and range is encouraged by the intensifying global rivalry. To put it briefly, the issue facing the aerospace sector is to create innovative materials that are at the same time safer, lighter, stronger, and more economical (18). Now is the time might be able to produce almost ideal materials with nanotechnology for space exploration and tourism, improving performance and passenger safety while saving a substantial amount of money and the environment.

In conclusion, research on the development of nanotechnology in the fields of aerospace and aeronautics has substantially enhanced.

The understanding of the effect of nanomaterials on the fuselage of spacecraft and aircraft, green development of fuels, sustainable implementation of nanotechnological advancements to jet engines, and analysis of the aerospace market for sustainable and friendly advancements. The paper highlights spacecraft components and nanomaterials, which are composite materials for the manufacturing of future spacecraft and aircraft. Furthermore, research specifies a faster, cheaper, and more efficient way of space transportation, which is by using carbon nanotubes and specific launch advances that need to be accounted for before takeoff. The study also demonstrates the future of nano sensors and scenarios for astronaut or pilot emergencies, and how sensors and AI can react in such situations. MEMS systems are discussed from a broader view and understanding. Research considers using thrusters and adjusting more or less of the MEMS unique food for different spacecraft, rather than designing and manufacturing separate engines and motors for spacecraft. In short, nanotechnology has opened the door for the use of numerous lighter, yet more effective, materials for aircraft and spacecraft, which would reduce the environmental impact of space tourism.

4.2. Occupational and In-flight Health Risks

Airborne particles with a diameter of less than 100 nm are thought to be very harmful to human health, and air pollution is one of the most serious environmental health risks. For reasons that are still unclear, their origin, among other factors, influences their inherent toxicity. They are created by a variety of sources, including internal combustion engines, burning wood and biomass, and burning fuel and natural gas. The aerosol fraction contains gaseous pollutants, including NOx, SO_2, and ozone, and many of the nanoparticles' constituents are toxic or at least dangerous, such as heavy metal compounds and polycyclic aromatic hydrocarbons (PAHs). These substances can all lead to oxidative stress, mitochondrial damage, lung and other tissue inflammation, and damage to cellular organelles. Airborne pollution may have an impact on the neurological, cardiovascular, and respiratory systems, according to epidemiological studies. Furthermore, the cellular inflammatory re-sponse to the pollutants, in which the release of cytokines encourages the multiplication of pre-existing mutant cancer cells, has been connected to particulate matter's increased risk of lung cancer. This carcinogenic effect is not related to DNA damage. Using animal models or cell cultures, the mechanisms underlying toxicity can be empirically examined. Although several approaches to collecting particulate matter have been investigated, consistent procedures are required to guarantee that the samples correctly reflect chemical combinations found in the environment. Nanoparticle toxic components can be investigated in cellular and animal models; however, it might be difficult to provide realistic exposure conditions. By simulating the intake of particles into the lungs, the air–liquid interface (ALI) device exposes cells directly. To comprehend the effects of nanoparticles and other air-borne pollutants and to create proactive measures to reduce the hazards they pose to human and environmental health, ongoing study and monitoring are crucial (26).

The number of people living in urban regions has doubled worldwide between 1950 and 2018, and by 2023, 4.4 billion people—or 55% of the world's population—will be urban dwellers. By 2050, the UN predicts that the tendency will have increased to 68%. As the urban population continues to rise, Urban Air Mobility (UAM) is one of the key technologies that is anticipated to help develop solutions. Either hybridized or fully zapped control makes the propellers more energetic. Unmanned Aerial Systems are currently being used extensively for observation and recording, and their importance in the context of UAM is growing. Given their operational requirement to vertically take off and arrive within "vertiports" established in densely populated cities, future UAM systems will unavoidably be accompanied by innovative impetus design, such as a cluster of distributed drive frameworks (DPS), multi-rotor arrangements, as well as AI and nanotechnology. Nanotechnology is and will be widely used in the manufacturing of aerial vehicles and UAM systems, such as civil tiltrotor. Nanomaterials such as carbon-polymer nanocomposites and CNTs for sensing and actuation in unmanned systems, and chitosan-based nanoparticles may be applied in the delivery systems. Additionally, nanotechnology plays a vital role in enhancing the performance of the communication and digitalization systems used for navigation, tracking, and data services, such as vision-based navigation in UAM and 6G networks. Permissioned blockchains and smart contracts are used to enhance the data security of aerial vehicles and UAM (27).

4.3. Future Pathways in the Implementation of AI and Nanotechnology

The growing intersection of AI and nanotechnology presents several difficulties as well as new research opportunities. This convergence relies heavily on interdisciplinary collaboration, which brings together specialists from a variety of disciplines, including computer science, medicine, and materials science. Although it can be extremely difficult, closing the knowledge gap between these fields is crucial to the effective creation of novel solutions. The quantity and quality of the data present a significant obstacle in this convergence. Large, high-quality datasets are essential for AI systems to flourish. Getting enough data can be a problem in many uses of nanotechnology. For reliable AI-driven solutions, it is essential to guarantee data accessibility, diversity, and accuracy. The quantity and quality of the data present a significant obstacle in this convergence. Large, high-quality datasets are essential for AI systems to flourish. Getting enough data can be a problem in many uses of nanotechnology. For reliable AI-driven solutions, it is essential to guarantee data accessibility, diversity, and accuracy. Data privacy, intellectual property rights, and fair access to AI-driven inventions are among the ethical issues brought up by the responsible application of AI in nanotechnology. In addition to fostering public trust, addressing these ethical concerns is crucial to ensuring the equitable and responsible use of developing technology. Regulations frequently find it difficult to keep up with the quick advancements in nanotechnology and artificial intelligence. To maintain safety, security, and moral standards in these developing industries, governments and international organizations must adjust and enact rules. AI-driven nanomanufacturing procedures and nanodevices can be expensive and difficult to scale up for real-world uses. A constant issue is achieving scalability without sacrificing accuracy and effectiveness. Hence, security and privacy issues become increasingly pressing. It is essential to mitigate security flaws and protect data privacy to stop abuse and online threats. Future developments in science and technology will continue to be influenced by the convergence of AI and nanotechnology. To traverse this changing world, ethical principles, standards, and best practices for responsible AI use will be crucial. AI-driven materials will also enable the development of new nanomaterials with specialized features, which will help various fields (28).

SUMMARY

These days, nanotechnology has provided an enormous benefit to the aviation and aerospace industries for improved manufacturing, spacecraft, fuels, health, and more. The objective of this paper is to review and propose a higher level of nanotechnology development in the aviation industry. While space exploration and tourism have sparked an appreciation for Earth's environmental changes from space, numerous criticisms have highlighted the significant negative impact that space travel has had on the environment. Here, nanotechnology is offered as a field that can both improve space tourism and decrease its impact on the Earth's environment. Specifically, this paper starts with a review of what material properties are needed for space exploration and then suggests the use of nanotechnology in the development of improved composite materials for jet engines, propulsion, and durability, considering the aeronautical standards and aerospace developments, introducing the implementation of artificial intelligence (AI). This research includes aerospace and aeronautical industry manufacturers, their new nanotechnological strategies and breakthroughs, as well as failed attempts during manufacturing or operations. Addressing the failures, this research indicates possible future steps for developing nanotechnology in unmanned and manned aircraft to reduce harm to the environment while still achieving space exploration. Future ethical guidelines, standards, and best practices should direct the responsible application of AI in nanotechnology. Nanotechnology will be crucial in determining the direction of healthcare, environmental sustainability, and energy solutions in the future, while AI-driven materials discovery will continue to provide amazing breakthroughs. AI-driven quantum computing has the potential to completely transform various sectors and areas of research. In conclusion, human ingenuity and inventiveness are demonstrated by the merging of AI and nanotechnology. This convergence can easily change our world by tackling difficulties and moral dilemmas while pursuing state-of-the-art research and development. It could solve some of the most important problems of our day and open new horizons in knowledge, digitalization, innovation, and technology.

Investigation Tables

Table 1: Use of Nanotechnology in Aircraft and Aerospace (10)

Use of Nanotechnology in Aircraft	Aircraft parts and structures
Lightweight materials	Fuselage and fuel efficiency systems
Improved structural integrity	Aircraft construction (tensile strength)
Enhanced thermal protection	Sensitive electronic equipment
Anti-corrosion coatings	Paints, coatings, and resistance to oxidation & environmental degradation
Sensing and repair nanotechnology	Cracks, corrosion, and excessive heat

Table 2: Applications, Composite Materials, and Future Composite Nanomaterials for Aerospace Equipment

Aerospace equipment	Applications of the equipment in Aerospace	Composite materials	Future composite nanomaterials
Booster rockets	Space explorations	Titanium	Nano-titanium
Space balloon	Space travel	Carbon	Carbon nanotubes
Elevator physics	Space travel	Graphite	Graphene
Aircraft	Aeronautical transportation travel	Aluminum	Aluminum nanoparticles

Virgin Galactic	Space travel	Carbon	Carbon fiber
Spacesuit	Space travel operations	Nylon/Carbon	Nano Silicon Carbide
Space sensors	Spacecraft operations	Wires	Nanowires
Jet engines	Aircraft operations	Nickel	Nano Nickel

Table 3: Nano Chemistries and Applications in Space Exploration (25)

Chemistry	Application in Space Exploration
Interfacial chemistries	Stabilize the interfacial bonding between nanomaterials
Improved CNT nanocomposites	Crew habitats, space suits, scaled-up fabrication of CNT nanocomposites, and developing Silicon Carbide nanotubes
Biologically inspired materials	Discover novel biological materials and mimic desired properties
High-throughput methodology for nanomaterial design	Generate a wide variety of candidate nanomaterials and high-throughput screening
Bioinspired and self-reliable materials	Damage tolerance and sensing characteristics

V. FIGURE DEPICTIONS AND ANALYSIS

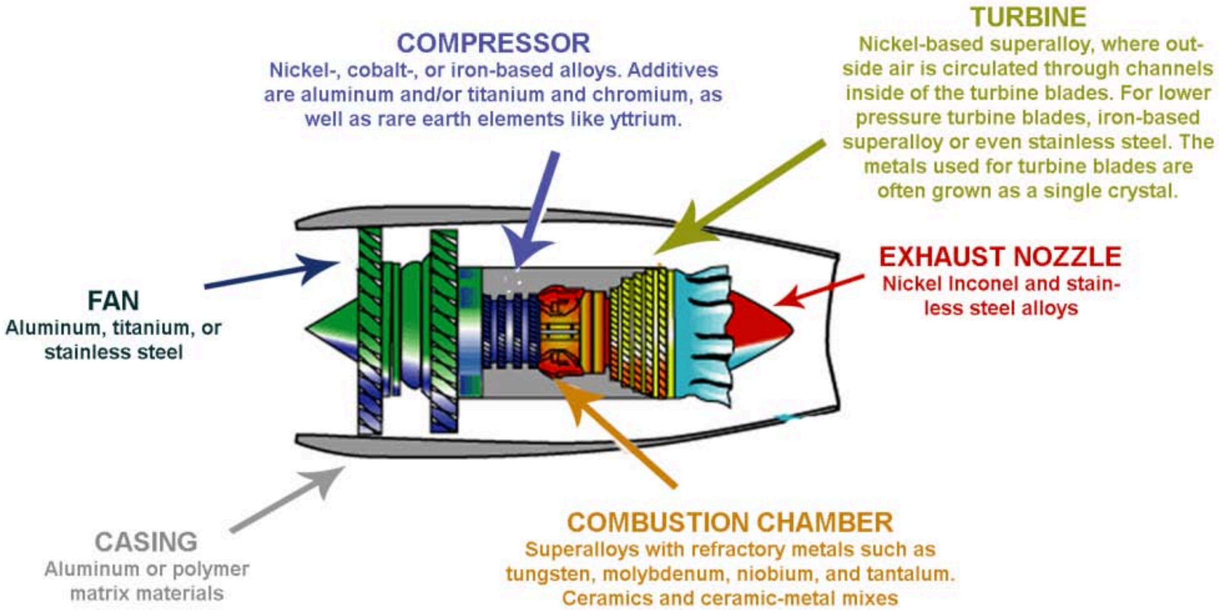
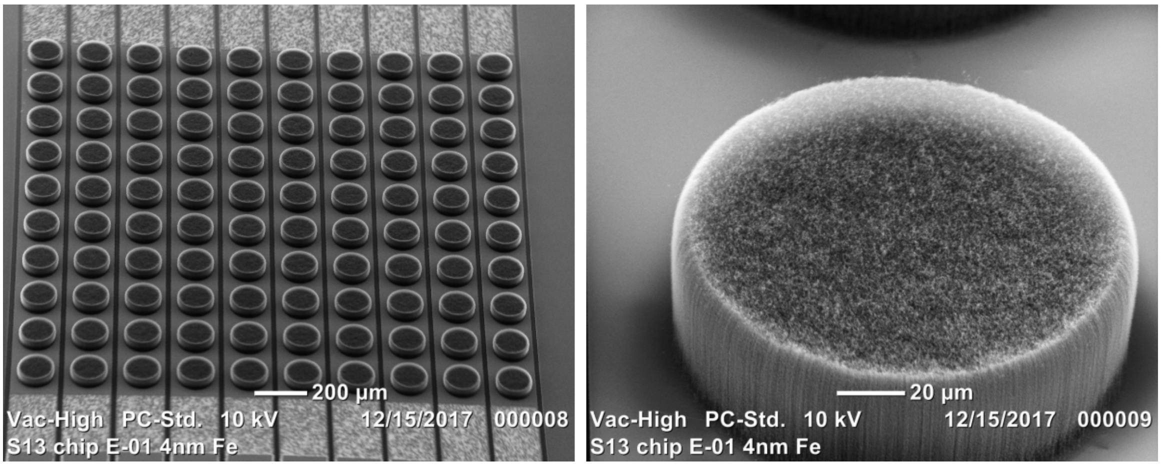


Figure 1: Proposed composite materials of a jet engine and areas of nanotechnological incorporation to reduce the impact on the environment. Reprinted with permission of the "PreScouter." (22)(23)

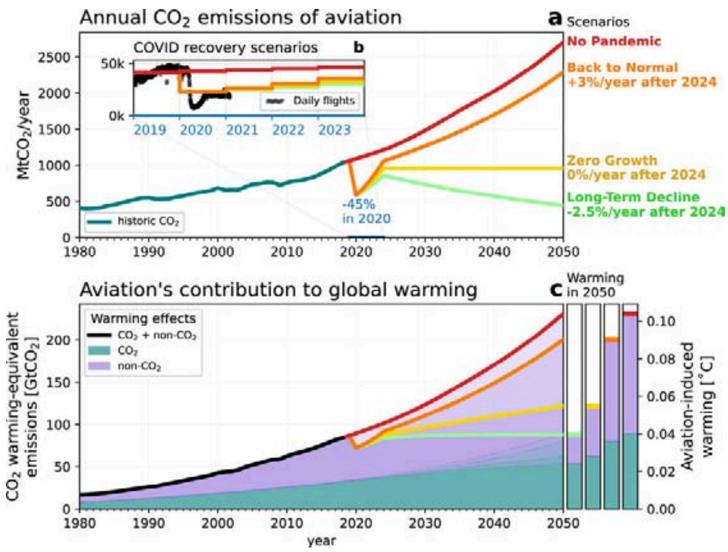


Credits: NASA (24)

Figure 2: Electron microscope images showing patterned nanotubes that would operate as an electron emitter in a new instrument now being developed for analyzing extraterrestrial samples. The right image is a close-up of one of the bumps. To create these highly versatile structures, technicians place a silicon wafer or some other substrate inside a furnace. As the oven heats, they bathe the substrate with a carbon feedstock gas to produce the thin coating of nearly invisible hair-like structures.

VI. GRAPHICAL AND TABLE ANALYSIS

(a) Annual historic and future annual carbon dioxide (CO2) emissions of aviation following four scenarios: No pandemic, back to normal, zero long-term growth, and long-term decline. (b) Daily flights of selected airports globally between 2019 and November 2020 and annual averages for all scenarios. (c) Cumulative warming-equivalent emissions of CO2 and non-CO2 effects of aviation since 1940 and the corresponding aviation-induced global warming. Scenarios are color-coded as in (a) (21).



Graph 1: Aviation's contribution to global warming till 2050

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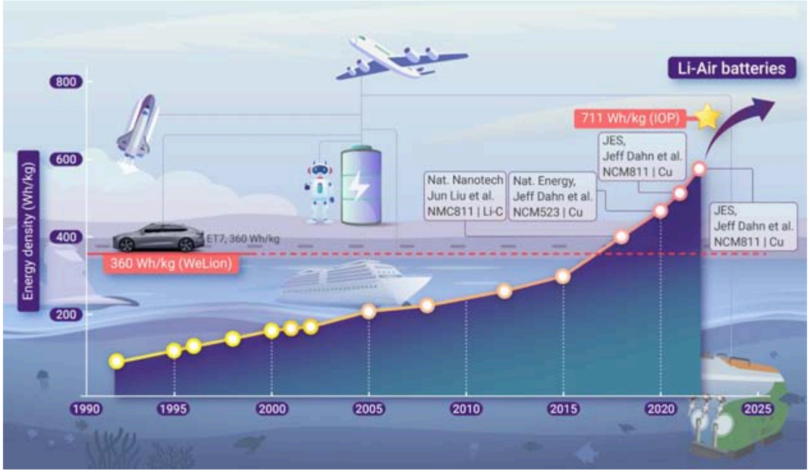

Graph 2: Road towards high-energy density batteries

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Evolution of Performance Metrics for Accurate Evaluation of Speech-to-Speech Translation Models: A Literature Review

Gabriel O. Sobola, Emmanuel Adetiba, Olabode Idowu-Bismark, Oluseyi O. Ajayi, Raymond Jules Kala, Abdul taofeek Abayomi, Oluwadamilola Oshin & Olutoyin Olaitan

Engineering Covenant University

ABSTRACT

The translation of speech from a source to speech in a target language with generative artificial intelligence is an area of research that is presently being actively explored. This is aimed at solving global language barriers thereby ensuring seamless communication between the individuals involved. It has been well developed for high-resourced languages like English, Spanish, French and Chinese. Currently, objective evaluation metrics such as Bilingual Evaluation Understudy Scores (BLEUS), and subjective metrics such as Mean Opinion Score Naturalness (MOSN) and Mean Opinion Score Similarity (MOSS) are being used to evaluate the performance of the output of speech-to-speech models. However, low resourced languages are still undeveloped in the area of speech processing applications, especially the African indigenous languages. The output speech in the target language needs to be evaluated to determine the closeness to the ground truth, as well as how natural and intelligible it is to the intended listeners.

Keywords: BERTscore, bilingual evaluation understudy scores (BLEUS), BLASER, leaderboards, mean opinion score naturalness (MOSN), mean opinion score similarity (MOSS), recall oriented understudy for gisting evaluation longest common subsequence (ROUGE-L), speech-to-speech metrics, word error rate (WER).

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Gabriel O. Sobola[α], Emmanuel Adetiba[σ], Olabode Idowu-Bismark[ρ], Oluseyi O. Ajayi[Ѡ], Raymond Jules Kala[¥], Abdul taofeek Abayomi[§], Oluwadamilola Oshin[χ] & Olutoyin Olaitan[ν]

ABSTRACT

The translation of speech from a source to speech in a target language with generative artificial intelligence is an area of research that is presently being actively explored. This is aimed at solving global language barriers thereby ensuring seamless communication between the individuals involved. It has been well developed for high-resourced languages like English, Spanish, French and Chinese. Currently, objective evaluation metrics such as Bilingual Evaluation Understudy Scores (BLEUS), and subjective metrics such as Mean Opinion Score Naturalness (MOSN) and Mean Opinion Score Similarity (MOSS) are being used to evaluate the performance of the output of speech-to-speech models. However, low resourced languages are still undeveloped in the area of speech processing applications, especially the African indigenous languages. The output speech in the target language needs to be evaluated to determine the closeness to the ground truth, as well as how natural and intelligible it is to the intended listeners. This paper presents a review of trends from the current metrics to emerging ones such as Recall Oriented Understudy for Gisting Evaluation-L (ROUGE-L) and BLASER. The applications of speech models' metrics on various leaderboards and modern AI platforms were also discussed. The outcome shows that while BLEU score and MOSN metrics are prevalent for speech models, there is a need to explore metrics such as ROUGE-L, and BERTScore which are machine translation metric due to their benefits.

Keywords: BERTscore, bilingual evaluation understudy scores (BLEUS), BLASER, leaderboards, mean opinion score naturalness (MOSN), mean opinion score similarity (MOSS), recall oriented understudy for gisting evaluation longest common subsequence (ROUGE-L), speech-to-speech metrics, word error rate (WER).

Author α σ ρ χ: Covenant Applied Informatics and Communications Africa Center of Excellence (CApIC-ACE) & Department of Electrical and Information Engineering Covenant University, Ota 112104, Nigeria.
σ: HRA, Institute for Systems Science, Durban University of Technology, Durban 4001, South Africa.
Ѡ: Department of Mechanical Engineering, Covenant University, Ota 112104, Nigeria.
¥: International University of Grand-Bassam, Grand- Bassam, Côte d'Ivoire.
§: Faculty of Engineering, Built Environment and Information Technology, Walter Sisulu University, Buffalo City Campus, East London 5200, South Africa & Department of Information Communication, Summit University, PMB 4412, Offa 250101, Kwara State, Nigeria.
ν: Department of Applied Informatics and Mathematical Sciences, Walter Sisulu University, 27, Nelson Mandela Drive, Mthatha 5100, South Africa.

I. INTRODUCTION

The translation of speech from one language, *the source*, to another language, *the target*, demands an efficient evaluation metric for its evaluation. Researchers in the area of speech processing applications are considering objective evaluation metrics such as the Word Error Rate (WER), Bilingual Evaluation

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Understudy (BLEU) scores, and BERTScore as well as subjective evaluation metrics such as the Mean Opinion Score (MOS) Naturalness and Similarity for evaluating the output of such models. Currently, there are no standard objective evaluation metrics applied directly to the generated output target speech [1]. This is because all objective evaluation demands speech output to be converted to texts. Hence, there are issues associated with such metrics. For instance, to utilise the BLEU score metric, the output speech needs to be transcribed to texts after which the texts are being compared or evaluated against the reference or ground truth texts. Researchers have observed overtime errors introduced in the obtained BLEU score due to the Automatic Speech Recognition (ASR) model utilised for such task. According to them, using an evaluation metric that takes the output target speech directly will be better than the ASR for computation of BLEU score. The ASR models have inherent errors that alter the expected metric result obtained using the BLEU score. To overcome this issue, some researchers have utilised large ASR models such as Whisper, based on large hours of data training to generate the transcripts to be compared with the ground truth [2 - 5]. Other researchers have also explored MOS Naturalness and MOS Similarity which are both subjective evaluation in conjunction with objective metrics. Here, raters are sourced to evaluate the performance of the generated output speech using their natural instinct to rate the speech model's output. Such metrics are being utilised to evaluate the fluency, accuracy, quality, and correctness of the generated speech, and the ratings are based on human judgments. To further enhance the objective evaluation metrics, it was confirmed in [1] that character-based performance metrics like character-based F1 score (chrF), and character-based BLEU score (chrBLEU) [6] are more robust metrics for speech-to-speech translation and speech synthesis tasks [1]. They were discovered to show a high correlation with human judgment than BLEU and MCD [1]. Some state-of-the-art speech-to-speech translation models such as Whisper [26], Translatotron, Translatotron2, SeamlessM4T and AudioPalm, and speech models developed by other researchers have utilised the aforementioned metrics to evaluate their models.

Metrics such as the Metric for the Evaluation of Translation with Explicit Ordering (METEOR) [1] that shows high correlation with human judgment [7], ROUGE – L, and BLASER have found low utilisation for computation of speech model evaluation. METEOR, ROUGE - L are mostly utilised for texts summarisations, and other Natural Language Processing (NLP) tasks such as machine translation and question answering [7]. Translation Error Rate (TER) is another metric for machine translation [7] which could be explored for speech-to-speech translation tasks [8] as it could be used to evaluate the texts equivalents of the target speech. As a result, it is suggested that researchers could explore ROUGE-L for the speech-to-speech translation tasks since it is evaluated on the texts obtained from generated target speech. The ROUGE – L is a metric that makes use of non-contiguous subsequence obtained from both the predicted texts and ground truth texts by comparing the two texts. It has been shown to have relationship with the well-known statistical metrics such as precision, recall, and f1-scores, by setting the beta parameter in its formula. Other variants of ROUGE such as the ROUGE-S, and ROUGE-W (ROUGE-Weighted) [9] have performed successfully in machine translation tasks [7, 9]. Other common ROUGE used in translation tasks are ROUGE-WE (ROUGE-Word Embedding), ROUGE-G (ROUGE-Graph based) and ROUGE-1, ROUGE-2 [7]. WER, an objective evaluation is mostly utilised for Automatic Speech Recognition (ASR) where the transcribed texts are compared with the reference texts. In addition to this is the BERTScore that is mostly utilized for machine translation models. This has been confirmed to perform better than ROUGE-L, METEOR, and BLEU score due to its high similarity measure between the candidate (machine translated output) and reference or ground truth samples using the cosine similarity procedure [7]. However, it lacks word ordering. It can also be utilized for speech-to-speech translation model by using the transcribed texts rather than the target speech obtained. There is also Cross Lingual Semantic Textual Similarity (XSTS) [10-11], a human metric that measures semantic similarity between a source speech and target translation. At present, more AI platforms and leaderboards are being engaged in the areas of the Natural Language Processing

(NLP) to rate and compare AI models. Some are known to speech models to evaluate the performances of various SOTA models. Examples of such are the Hugging Face Leaderboards, IWSLT Challenge etc. [45-50] and some are specifically for speech-to-speech translation models. Each platform has its own metrics used to evaluate speech models. Going by the aforementioned, there are numerous metrics/models that have been used in the past and are currently being engaged with varying performance levels. Hence, there is a need to evaluate the performance of some of the models to ascertain their efficiency. This is the basis for this study. Various metrics that are used in speech-to-speech translation tasks and speech processing applications were reviewed with a view to comparatively determining their efficiencies.

II. PERFORMANCE METRICS

The evaluation of speech-to-speech translation models are either carried out on the target output speech (Subjective evaluation), transcribed texts of the target output speech using an ASR model (objective evaluation), or spectral representations of the target output speech. At other times, the evaluation could be carried out in subjective approach in terms of comparing the target output speech with the source speech as in the case of Cross Lingual Semantic Textual Similarity (XSTS). Others are statistical evaluation metrics such as Accuracy, Precision, Recall, and F1-Score.

2.1 Subjective Performance Metrics

In this evaluation metrics, raters are hired to judge the output speech obtained from the speech-to-speech model. In order words the evaluation is performed directly on the speech obtained. Examples of such metrics are MOS Naturalness, MOS Similarity, XSTS etc.

2.1.1 Mean Opinion Score (MOS)

This is a subjective performance metric that is based on the judgment made by the observer on the output translated speech of the target language. It is the most utilised for speech- to-speech evaluation metric [3]. It could be MOS Naturalness or MOS Similarity. In this type of subjective evaluation, raters are sought, who then score the output generated speech on a scale from 1 to 5 which could be 1 = Poor, 2 = Satisfactory, 3 = Good, 4 = Very good, and 5 = Excellent.

2.1.1.1 Mean Opinion Score (MOS) Naturalness

In MOS Naturalness, the raters judge the quality, naturalness, and appropriateness of pro nunciation of the speech output on a scale of 1 to 5. In this case, an incorrectly translated natural target output speech will be rated higher [2] when compared with a correctly unnatural target output speech.

2.1.1.2 Mean Opinion Score Similarity

In MOS Similarity, the raters score the output speech obtained by comparing it with a reference or ground truth output (which can be human-generated speech or synthesised) on a scale of 1 to 5 using quality such as the fluency (flow or correctness of grammar), and adequacy (how deviated speech is from its intended meaning or deviation from the ground or reference speech) of the generated output speech.

2.1.2 Cross Lingual Semantic Textual Similarity (XSTS)

This is a subjective evaluation that is carried out by human raters to assess the quality of the translated target speech. It is conducted by comparing the adequacy (how close it is to its intended meaning) of the generated speech to the source speech. This implies that the human rater or judge must be bilingual to be able to access such target speech for its meaning. The human annotator judges the semantic similarity rather than fluency between the source and target speech [10-11]. Using a score on a scale of 1 to 5, the annotator assigned each language pair (source-translated target speech) for semantic meaning where a score of 3 or more indicates the two speeches are close in terms of meaning being conveyed. XSTS is a subjective evaluation metric that also checks for the audio quality as it is utilised directly on the audio generated output target speech. It was originally developed for texts evaluation [12]. To obtain the final XSTS results, an average value is computed across selected XSTS computed scores by the human annotators.

2.1.3 Blaser

This is a modality agnostic evaluation metric that works on both speech and texts [13-14]. A version of BLASER, BLASER 2.0 utilised in [14] was a modification on the first version [13]. For speech-to-speech translation tasks, it offers the advantage of being text-free unlike the ASR BLEU performance metric. For BLASER 2.0, the source speech, the translated target speech and the reference texts are converted into Sentence-level multimOdal and language-Agnostic Representations (SONAR) embedding vectors $(h_{src}, h_{mt}, \text{ and } h_{ref})$. These vectors are then fed into a small dense neural network for prediction of XSTS scores for each output of the translation for the supervised version of BLASER 2.0. For the unsupervised version, the cosine similarities between the source and target translated output is obtained for BLASER computation.

2.2 Objective Performance Metric

In the objective, the target output speech of the speech-to-speech translation model is fed to an ASR model to obtain the texts or transcripts equivalent of the speech. Evaluation is then performed on these texts to assess the performance of the model. Examples are the WER, BLEU Score, ROUGE-L, BERTScore, etc.

2.2.1 Bilingual Evaluation Understudy (BLEU)

This is an objective n-gram evaluation that involves the comparison of the speech target output with that of the reference or ground truth. To compute the BLEU score, the output of the speech translation is fed to an ASR model to generate the text equivalent. The texts generated are then compared with the ground truth texts, and the BLEU score is computed. Mathematically, the BLEU score is computed using equation (1) [15]:

$$BLEU\ score\ =\ BP\ *\ \exp exp\ \sum_{i=1}^{N} w_i p_i \tag{1}$$

where:

$$BP\ =\ Brevity\ Penalty\ =\ \exp exp\left(1\ -\ \frac{r}{c}\right) \tag{2}$$

which is also computed as:

$$BP\ =\ Brevity\ Penalty\ =\left(1,\ \frac{r}{c}\right) \tag{3}$$

$r\ =\ length\ of\ machine\ translated\ output\ (text\ or\ speech)$
$c\ =\ length\ of\ reference\ translation\ (text\ or\ speech)$
$p_i = n\ -\ \ gram\ modified\ precision\ score\ of\ order\ i,\ which\ is\ given\ in\ equation\ (4)\ as:$

$$p_i = \frac{Count\ Clip\ (matches, max-reference-count)}{candidatae\ n-gram} \tag{4}$$

$N = maximum\ number\ of\ n - gram\ order\ to\ consider\ (usually\ up\ to\ 4)$

$w_i = weight\ for\ n - gram\ precision\ of\ order$

2.2.1.1 Evaluation of BLEU Score Computation

Given the information below for both the machine-translated output (obtained using ASR) and reference output text:

Machine Translation (MT): The picture the picture by me.
Reference (Ref) 1: The picture is clicked by me.
Where:
$r = 6$
$c = 6$
The n-gram modified precision score of order *i*, as depicted in equation (4) is computed using Table 1.

Table 1: A summary results for the Computation of n-gram Modified Precision Score

n = 1				n = 2				n = 3				n = 4			
	MT l = 6	Ref r = 6	Min (MT, Ref)		MT	Ref	Min (MT, Ref)		MT	Ref	Min (MT, Ref)		MT	Ref	Min (MT, Ref)
“the”	2	1	1	“the picture”	2	1	1	“the picture the”	1	0	0	“the picture the picture”	1	0	0
“picture”	2	1	1	“picture the”	1	0	0	“picture the picture”	1	0	0	“picture the picture by”	1	0	0
“by”	1	1	1	“picture by”	1	0	0	“the picture by”	1	0	0	“the picture by me”	1	0	0
“me”	1	1	1	“by me”	1	1	1	“picture by me”	1	0	0				
$p_1 = \frac{4}{6} = \frac{2}{3}$				$p_2 = \frac{2}{5}$				$p_3 = \frac{0}{4} = 0$				$p_4 = \frac{0}{3} = 0$			

Hence, using equation (3), the Brevity Penalty is computed as:

$$BP = \left(1,\ \frac{r}{c}\right) = \left(1,\ \frac{6}{6}\right) = (1,\ 1) = 1$$

Substituting BP with other parameters into equation (1) gives:

$$BLEU\ score = BP * \exp exp \sum_{i=1}^{N} w_i p_i$$

$$BLEU\ score = 1 * \exp exp \sum_{i=1}^{4} w_i p_i$$

$$BLEU\ score = 1 * \exp exp\ (0.25\frac{2}{3} + 0.25\frac{2}{5} + 0 + 00)\ [w_1 = w_2 = 0.25,\ w_3 = 0,\ w_4 = 0];$$

$$BLEU\ score = 0.718 = 71.8$$

2.2.1.2 Character-level BLEU (charBLEU)

This is a BLEU score metric that computes the BLEU score on the character level rather than on the sentence level [6]. It is a better evaluation metric than the ASR BLEU score.

2.2.1.3 Weaknesses of BLEU Score

1. It is an n-gram precision-based metric that does not take into consideration the recall, and its reliance on the exact matching of the n-gram [7].
2. It does not show correlation when compared with human judgment for speech-to-speech translation tasks [7].

2.2.2 Word Error Rate (WER)

For speech-to-speech translation tasks, the WER, an objective evaluation for comparing the ground truth word string to machine translated word string is obtained using equation (5) [16-17] as:

$$WER = \frac{S+D+I}{N} \tag{5}$$

where:

$S = The\ number\ of\ substitutions$
$D = The\ number\ of\ deletions$
$I = The\ number\ of\ insertions$
$N = The\ number\ of\ words\ in\ the\ reference$

2.2.2.1 Computation of WER in Speech-Speech Translation

Given the reference text (ground truth) of the target language (Yorùbá) as GT and the Translated text equivalent of the translated speech of the target language (Yorùbá) of the output of the translator as MT as given below, the WER is computed using equation (13) as illustrated below:

GT: *A bẹ̀rẹ̀ ìmúlò àjẹsára ibà pọ́njú − pọ́ntọ̀ ní ọdún* 1938.

MT: *A bẹ̀rẹ̀ ìmúlò àwọ́n àjẹsá ibà pọ́njú − pọ́ntọ̀ ọdúni .*

The *WER* is computed using equation (13) as:

$S = 2$ [*àjẹsá for àjẹsára and ọdúni for ọdún*
$D = 2$ [*ní and* 1938 *deleted in the MT obtained from ASR* (*input from target speech output*)]
$I = 1$ [*àwọ́n inserted in the MT output*]
$N = 9$

$$WER = \frac{S+D+I}{N} = \frac{2+2+1}{9} = \frac{5}{9} = 0.55$$

2.2.3 Recall-Oriented Understudy Gisting Evaluation (ROUGE – L)

This is an evaluation metric that compares the machine translated text sequence (ASR output obtained from speech audio output) with that of the ground truth text sequence by finding the Longest Common Subsequence (LCS) of words. It is mostly used in texts summarisation models like the GPT-4 [18] as well as machine translation [7]. According to findings it is much more efficient to compute the non-contiguous LCS of words than its contiguous counterpart to capture more flexible matches between the ground truth and machine translation texts as the order of words may be different. Statistical metrics such as precision, recall and f1 score can be computed using the LCS of both the ground truth word strings and machine translation word strings.

Given that:

$X = Reference\ or\ ground\ truth\ word\ or\ sequence$

$Y = Machine\ Translation\ word\ or\ sequence\ output$

$LCS(X, Y) = LongestCommon\ Subsequence\ of\ X,\ and\ Y\ (non\ contiguous)$

The statistical metrics are computed as giving in equations (6) to (8) follows [9]:

$$precision,\ p = \frac{len(LCS(X,Y))}{len(Y)} \tag{6}$$

$$recall,\ r = \frac{len(LCS(X,Y))}{len(X)} \tag{7}$$

$$f1 - score = \frac{((1+\beta^2) * p * r)}{(r+(\beta^2 * p))} \tag{8}$$

where:

$len(LCS(X, Y)) = Length\ of\ the\ LCS\ of\ X,\ and\ Y$
$len(X) = Length\ of\ the\ ground\ truth\ word\ string\ or\ sequence$
$len(Y) = Length\ of\ the\ machine\ translated\ word\ string\ or\ sequence$

$\beta = Parameter\ that\ is\ chosen\ to\ compute\ the\ f1 - score\ and\ controls\ the\ trade - off\ between$

Note that setting $\beta = 1$ makes equation (8) equals equation (9) (for computation of the statistical, $f1$) as illustrated below:

$$f1 - Score = \frac{2*Precision*Recall}{Precision+Recall}$$

$$f1 - score = \frac{((1+1^2)*p*r)}{(r+(1^2*p))} \tag{9}$$

$$f1 - score = \frac{(2*p*r)}{(r+p)}$$

When the value of $\beta = 1$, the weight of recall, r is equal to that of the precision p. The value β can also be set below or above 1. When $\beta = \frac{1}{2}$, more weights are allocated to the precision, p and this applicable where precision, p is crucial and when $\beta = 2$, more weights are allocated to the recall and it is utilised where recall, r is crucial.

Note that β is also obtained using $\frac{p}{r}$ [9].

2.2.3.1 Computation of Statistical Metrics and F-Based ROUGE-L in Speech-Speech Translation

Given the reference text (ground truth) of the target language (Yorùbá) as X and the Translated text equivalent of the translated speech of the target language (Yorùbá) of the output of the translator as Y as given below, the precision, recall, and F1-Score are calculated for ROUGE-L using equations (6-8) as illustrated below:

X: *A bẹ̀rẹ̀ ìmúlò àjẹsára ibà pọ́njú − pọ́ntọ̀ ní ọdún* 1938.

Y: *A bẹ̀rẹ̀ ìmúlò àjẹsá ibà pọ́njú − pọ́ntọ̀ ọdúni* 1938.

$LCS(X, Y) =$ *A bẹ̀rẹ̀ ìmúlò àjẹsá ibà pọ́njú − pọ́ntọ̀ ọdún* 1938. (*non contiguous subsequence*)
$len(X) = 9$

$len(Y) = 8$
$len(LCS(X, Y)) = 8$

$$precision,\ p = \frac{len(LCS(X,Y))}{len(Y)} = \frac{8}{8} = 1$$

$$recall,\ r = \frac{len(LCS(X,Y))}{len(X)} = \frac{8}{9} = 0.88$$

$$f1 - based\ ROUGE - L = \frac{((1+\beta^2) * p * r)}{(r+(\beta^2 * p))} = \frac{((1+1^2) * 1 * 0.88)}{(0.88+(1^2 * 1))} = \frac{2*1*0.88}{0.88+1} = \frac{1.77}{1.88} = 0.94$$

Note that in the first example given in this section using equations (6-8), the computation of precision, recall, and f1-score were carried out using word level counting and the parameter, $\beta = 1$

Considering the character level ROUGE – L computation, the following is obtained:

$len(X) = 50$
$len(Y) = 46$
$len(LCS(X, Y)) = 45$

Note that all characters such as alphanumerical, and special characters as well as white spaces are counted as characters.

$$precision,\ p = \frac{len(LCS(X,Y))}{len(Y)} = \frac{45}{46} = 0.97$$

$$recall,\ r = \frac{len(LCS(X,Y))}{len(X)} = \frac{45}{50} = 0.90$$

$$f1 - based\ ROUGE - L = \frac{((1+\beta^2) * p * r)}{(r+(\beta^2 * p))} = \frac{((1+1^2) * 0.97 * 0.90)}{(0.90+(1^2 * 0.97))} = \frac{2*0.97*0.90}{0.90+0.97} = \frac{1.746}{1.870} = 0.93$$

2.2.3.2 Advantages of using ROUGE-L for Speech-to-Speech Translation Model

The ROUGE-L score takes into consideration the longest common subsequence between the machine translated output and reference texts. This subsequence can either be contiguous or non-contiguous. For machine translation, utilising the contiguous nature of ROUGE-L ensures it avoids the consecutive matching of words for word level metric or consecutive matching of character for character level matching. This ensures it generalises across the whole texts capturing differences between the machine generated and ground truth texts. For speech-to-speech translation models, it could be used in integration with BLEU, and METEOR to enhance the translation model performance since it is possible for two different texts (sharing relationship to the ground truth text) to have same ROUGE-L score when compared to the ground truth texts [9]. In addition to that, the ROUGE-L score can also be utilised for assessing the quality of the translated texts which is essential in speech-to-speech translation tasks.

2.2.3.3 Limitation of using ROUGE-L for Speech-to-Speech Translation Model

ROUGE-L being a text-based metric, shows it has the capability to introduce errors typical of text-based speech processing metrics that could affect the performance of the model developed. Another limitation to utilising ROUGE-L is its usage in evaluating or comparing two similar machine translated texts obtained from two different models when compared to the ground truth texts. This is because, ROUGE-L cannot tell which one is close to the ground truth, rather it is an analytical approach to computing the performance metric. Such a limitation could be handled by the subjected evaluation using MOSN or MOSS where raters rate the speech output directly. In addition to that, ROUGE-L is not suitable for evaluating the naturalness, or quality of speech as this can be harnessed from the speech translated output. It is only used to evaluate the quality of the texts which may have deviated from the original speech due to ASR errors.

2.2.4 Mel-Cepstra Distortion (MCD)

This is a performance metric that compares the predicted target mel-cepstra with the reference mel-cepstra [19]. It is calculated as the difference between the MFCCs of the predicted target and reference audio. Mathematically, it is represented in equation (10) as proposed by [20]:

$$MCD_k = \frac{1}{T}\sum_{t=1}^{T}\sqrt{\sum_{k=1}^{K}(m_{tk} - \hat{m}_{tk})^2} \tag{10}$$

where:

m_{tk} = kth MFCC of the $t - th$ frame from the reference audio

$\hat{m}_{tk}$ = kth MFCC of the $t - th$ frame from the predicted audio

Then, MCD_k is the sum of the squared differences over the first K MFCCs. When the length of the two MFCCs sequences are not equal, Dynamic Time Warping (DTW) is utilised to compute the minimum distance MCD obtainable [19-21]. This is used to evaluate speech synthesis models.

2.2.5 BERTScore

This is language generation [39] evaluation metric that is mostly utilized for machine translation. It can also be utilized for speech-to-speech translation models by feeding the output speech obtained to an ASR model and then compares the texts obtained with the reference texts. BERTScore is based on pretrained BERT contextual embeddings. Hence, it computes the cosine similarity of the machine translation texts and ground truth or reference texts-this it does by finding the sum of the cosine similarity between their respective token's embeddings [39]. BERTScore was known to perform better than n-gram metrics such as BLEU score, METEOR, as well as ROUGE-L in machine translation [7]. It addresses two major problems associated with n-gram metrics, which are penalizing semantical-ordering of words, inability to capture distant dependencies, and their inability to match paraphrases. It was confirmed to have evaluation performance close to human judgement [39].
Given:

The reference / ground truth parameters as:

Tokenized sentence: $y = (y_1, y_2, y_3, y_4, ..., y_k)$
Embedding vectors of y: $Y = (Y_1, Y_2, Y_3, Y_4, ..., Y_k)$

The machine translated output parameters as:

Tokenized sentence: $\hat{y} = (\hat{y}_1, \hat{y}_2, \hat{y}_3, \hat{y}_4, ..., \hat{y}_m)$
Embedding vectors of y: $\hat{Y} = (\hat{Y}_1, \hat{Y}_2, \hat{Y}_3, \hat{Y}_4, ..., \hat{Y}_m)$,

The recall, precision, and F1-score are computed for BERTScore using equations (11-13) as [39]:

$$R_{BERT} = \frac{1}{|y|} \sum_{y_i \epsilon y} Y_i^T \hat{Y}_j \tag{11}$$

$$P_{BERT} = \frac{1}{|\hat{y}|} \sum_{\hat{y}_j \epsilon \hat{y}} Y_i^T \hat{Y}_j \tag{12}$$

$$F_{BERT} = \frac{2 * P_{BERT} * R_{BERT}}{P_{BERT} + R_{BERT}} \tag{13}$$

The computed BERTScore of equations (11-13) are within the cosine similarity range of -1 to 1, which does not affect human correlation or ranking of BERTScore. To ensure human readability, the range is adjusted to fall within 0 and 1. This is carried using empirical lower bound, b that is computed using Common Crawl monolingual datasets. The rescaled BERTScores for equations (11-13) are computed using equations (14-16) as [39]:

$$\hat{R}_{BERT} = \frac{R_{BERT} - b}{1 - b} \tag{14}$$

$$\hat{P}_{BERT} = \frac{P_{BERT} - b}{1 - b} \tag{15}$$

$$\hat{F}_{BERT} = \frac{F_{BERT} - b}{1 - b} \tag{16}$$

It is to be noted that scaling carried out above is an optional step. Prior to this step, another optional step that involves weighting with Inverse Document Frequency (IDF) score can also be done to obtain the weighted BERTScores instead of equation (11-13).

2.2.5.1 Pseudo Code for the Computation of BERTScore for Speech-to-Speech Translation Model

A. Pseudo code for BERTScore (Precision BERTScore)

1. *Begin*
2. Compute the tokenised sequences y, and $\hat{y}$ of both the reference texts and machine translation respectively.
3. Compute the embeddings Y and $\hat{Y}$ of both the reference texts and machine translation respectively.
4. For the first word $\hat{y}_1$ in the machine translation, compute the cosine similarity between its embedding, $\hat{Y}_1$ and all embeddings Y_1, Y_2, Y_3, Y_4, ..., Y_k in the reference texts.
5. Compute the maximum value given as: $Y_i^T \hat{Y}_j$
6. Repeat step 5 for the remaining words $\hat{y}_2$, $\hat{y}_3$, $\hat{y}_4$, ..., $\hat{y}_m$ in the machine translated output.
7. Compute the sum of the results of step 5 and 6 as: $\sum_{\hat{y}_j \epsilon \hat{y}} Y_i^T \hat{Y}_j$
8. Divide the result of step 7 by the total number of tokens in the machine translation output (candidate output) given by $\frac{1}{|\hat{y}|} \sum_{\hat{y}_j \epsilon \hat{y}} Y_i^T \hat{Y}_j$ to obtain P_{BERT}.

9. Compute the optional scaling precision score using: $\hat{P}_{BERT} = \frac{P_{BERT}-b}{1-b}$
10. *End*

B. Pseudo code for BERTScore (Recall BERTScore)

1. *Begin*
2. Compute the tokenised sequences y, and $\hat{y}$ of both the reference texts and machine translation respectively.
3. Compute the embeddings Y and $\hat{Y}$ of both the reference texts and machine translation respectively.
4. For the first word y_1 in the reference texts, compute the cosine similarity between its embedding, Y_1 and all embeddings $\hat{Y}_1$, $\hat{Y}_2$, $\hat{Y}_3$, $\hat{Y}_4$, ..., $\hat{Y}_m$ in the machine translated output.
5. Compute the maximum value given as: $Y_i^T\hat{Y}_j$
6. Repeat step 5 for the remaining words y_2, y_3, y_4, ..., y_k in the reference texts.
7. Compute the sum of the results of step 5 and 6 as: $\sum_{y_i \epsilon y} Y_i^T\hat{Y}_j$
8. Divide the result of step 7 by the total number of tokens in the reference texts given by $\frac{1}{|y|} \sum_{y_i \epsilon y} Y_i^T\hat{Y}_j$ to obtain R_{BERT}.
9. Compute the optional scaling recall score using: $\hat{R}_{BERT} = \frac{R_{BERT}-b}{1-b}$
10. *End*

2.2.6 Real Time Factor (RTF)

This metric is utilised to calculate the performances of ASR models. It measures the processing speed of audio. A higher RTF value shows a faster processing of audio signals. Mathematically, it is computed as the ratio of processing time to audio duration given in equation (17) as [61, 62]:

$$REAL - TIME\ FACTOR\ (RTF) = \frac{Processing\ Time}{Audio\ Duration} \tag{17}$$

2.2.7 Sort-Time Objective Intelligibility (STOI)

This metric measures the intelligibility of the speech signals. It can be used to evaluate how clean a speech signal is from its degraded replica. It is mostly utilised for text-to-speech models. For speech-to-speech translation task, it can be utilised to find how intelligible the target speech is from its reference speech. It is measured on a scale of 0 to 1 where 0 denotes unintelligibility while 1 means perfect intelligibility. The steps to compute the STOI of a speech signals are as follows [60]:

2.2.7.1 Steps to Compute the STOI of Speech Signal

1. Split the speech signals into short-time frames which is typically between 32 – 64 ns (256 – 512 samples with 50 % overlaps.
2. Calculate the Sort-Time Fourier Transform (STFT) for both the clean and degraded speech signals of each frame.

3. Compute the spectral magnitude of the STFT for each frame of both the clean and degraded speech signals.
4. Normalize the calculated spectral magnitude to have the same energy in each frame for both the clean and degraded speech signals.
5. Compute the correlation coefficients between the clean and degraded speech signals for each frame.
6. Calculate the STOI score by finding the average of step 5 across all frames.

2.2.8 Perceptual Evaluation of Speech Quality (PESQ)

This measures the quality of speech signals obtained from speech models. It is mostly used for speech synthesis models. It can also be used for speech-to-speech translation models. It measures speech quality on a scale of -0.5 to 4.5 where a higher score means better speech quality. A PESQ of -0.5 means bad speech quality while 4.5 PESQ denotes excellent speech [59, 63].

2.2.8.1 Steps to Compute the PESQ

1. Pre-process the clean and degraded speech signals (reference and target speech in the case of speech models) using pre-processing techniques such as filtering, and normalization.
2. Carry out time alignment of both the degraded and clean speech to check for any distortions or delays.
3. The disturbance or degradation which is the difference between the clean and target speech signals is computed.
4. Mapping of the disturbance to a PESQ score that ranges from -0.5 to 4.5 to calculate the score.

2.3 Statistical Evaluation

This refers to the utilisation of machine learning evaluation metrics. This involves Precision, Recall, F1-Score, etc.

2.3.1 Accuracy

This is the ratio of the sum of True Positive (TP) and True Negative (TN) to the sum of TP, TN, False Positive (FP), and False Negative (FN). It is obtained using equation (18) as [23]:

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (18)$$

2.3.2 Precision

This is the ratio of TP to the sum of TP and FP. Mathematically, it is obtained as given in equation (19) as [22-24]:

$$Precision = \frac{TP}{TP+FP} \quad (19)$$

Relating it to speech-to-speech translation tasks, it is computed using equation (20) as [25]:

$$Precision = \frac{No\ of\ correctly\ translated\ words\ (bold)}{Total\ number\ translated\ words} \quad (20)$$

2.3.3 Recall

This is the ratio of TP to the sum of TP and False Negative (FN). Mathematically, it is obtained as given in equation (21) [22-24]:

$$Recall = \frac{TP}{TP+FN} \tag{21}$$

For speech-to-speech translation tasks, it is computed using equation (22) as [25]:

$$Recall = \frac{No\ of\ correctly\ translated\ words\ (bold)}{Total\ number\ reference\ words} \tag{22}$$

2.3.4 F1-Score

This is the ratio of the product of precision and recall to the sum of precision and recall. Mathematically, it is obtained using equation (23) [22-24], which is same as equation (9) as:

$$F1 - Score = \frac{2*Precision*Recall}{Precision+Recall} \tag{23}$$

For speech-to-speech translation tasks, it is also computed using equation (9) which is same as equation (23).

2.3.5 Computation of Precision, Recall, and F1-Score in Speech-Speech Translation

Given the reference text (ground truth) of the target language (Yorùbá) as RT and the Translated text equivalent of the translated speech of the target language (Yorùbá) of the output of the translator as MT as given below, the precision, recall, and F1-Score are calculated using equations (19), (21), and (22) respectively as illustrated below [25].

RT/GT: A bẹ̀rẹ̀ ìmúlò àjẹsára ibà pọ́njú-pọ́ntọ̀ ní ọdún 1938.

MT: A bẹ̀rẹ̀ ìmúlò àjẹsá ibà pọ́njú-pọ́ntọ̀ ọdúni 1938.

$$No\ of\ correctly\ translated\ words\ (bold) = 6$$

$$Total\ number\ translated\ words\ in\ the\ output\ of\ the\ translator = 8$$

$$Total\ number\ of\ reference\ words = 9$$

$$Precision = \frac{No\ of\ correctly\ translated\ words\ (bold)}{Total\ number\ translated\ words} = \frac{6}{8} = 0.75$$

$$Recall = \frac{No\ of\ correctly\ translated\ words\ (bold)}{Total\ number\ reference\ words} = \frac{6}{9} = 0.66$$

$$F1 - Score = \frac{2*Precision*Recall}{Precision+Recall} = \frac{2*0.75*0.66}{0.75+0.66} = 0.702$$

III. COMPARATIVE ANALYSIS OF THE DIFFERENT EVALUATION METRICS

Table 2 shows the comparison of some of the speech-to-speech translation metrics so that researchers can make right choices for their speech-to-speech models. It details the subjective and objective evaluation metrics, such as MOS Naturalness, MOS Similarity, BLASER, & XSTS; and BLEU score, WER, METEOR, ROUGE-L, BERTScore, & MCD respectively. The table also highlights the statistical metric that could also be explored for speech-to-speech translation tasks [7, 9]. Table 3 gives highlights of when, application areas and how each of the discussed metrics are utilised.

Table 2: Comparison of Various Performance Metrics for Speech-to-Speech Translation Tasks

Evaluation Metrics	Application	Fluency	Adequacy	Audio translation quality	Naturalness
Subjective Evaluations					
MOS Naturalness	Target output speech			Excellent	Excellent
MOS Similarity	Target output speech	Excellent	Excellent		
BLASER	Target output speech			Excellent. It is text-free. [12]	
XSTS	Target output speech		Excellent	Excellent [12]	
Objective Evaluations					
BLEU score	Text obtained from Target output speech	Excellent [9]	Excellent [9]	Excellent [12]	
ROUGE-L	Text obtained from Target output speech	Excellent	Good		
WER	Text obtained from Target output speech	Excellent [9]	Good [9]		
MCD	Cepstral features of both source and target speech			Excellent	
Statistical Metrics (precision, recall, and f1-score)	Text obtained from Target output speech	Excellent	Good		
METEORS	Text obtained from Target output speech	Excellent [7]		It has high correlation with human judgment.	It has high correlation with human judgment.
BERTScore	Text obtained from Target output speech	Excellent	Excellent		

Table 3: When, where, and how to use the Speech Translation Metrics

Performance metrics	When	Where	How
MOS Naturalness	1. Fluency, adequacy, and audio quality are needed.	Speech-to-speech translation, automatic speech translation, speech synthesis tasks	Sourcing human raters to judge the target speech using a scale of 1 to 5 where 1 = Poor, 2 = Satisfactory, 3

			= Good, 4 = Very good, and 5 = Excellent.
MOS Similarity	1. Fluency, adequacy, and audio quality are needed.	Speech-to-speech translation, automatic speech translation, speech synthesis tasks	Same as above
BLASER	1. Audio quality is to be tested.	Speech-to-speech translation tasks	Translated output speech is converted into vectors and the vectors are then fed into a small dense neural network for prediction of XSTS scores for each output of the translation for the supervised version of BLASER 2.0
XSTS	1. Adequacy, and audio quality are needed.	Speech-to-speech translation tasks.	It is used by human raters who are bilingual and judge how adequate the target speech is to be source speech on using a score on a scale of 1 to 5.
BLEU score	1. Fluency, adequacy, and audio quality are needed.	Speech-to-speech translation, automatic speech translation, speech synthesis, machine translation tasks	Computed on n-gram words, and evaluated using equations (1) to (4)
ROUGE-L	1. Non-contiguous subsequence order of words or character is needed. 2. Quality of texts is needed.	Speech-to-speech translation, machine translation, texts summarisation	Computed on word-to-word matching. It is evaluated using equations (6) to (9)
WER	1. Quality of texts is needed.	Speech-to-text, text-to-speech, speech-to-speech translation tasks.	Computed on texts using equation (5)
MCD	1. Audio quality is needed.	Speech synthesis tasks	Computed on texts using equation (10)
Statistical Metrics (precision, recall, and f1-score)	1. Quality of texts is needed.	Speech-to-speech translation tasks,	Computed on texts using equation (17) to (22)
METEORS	1. When word-to-word matching is needed between the reference and machine translated output. 2. Word order is needed.	Speech-to-speech translation tasks	Computed on the texts obtained from the ASR output fed with target speech.
BERTScore	1. Word ordering and capturing of dependencies is needed. 2. A good score for paraphrasing is needed.	Speech-to-speech translation tasks, sentence summarizations,	Computed on the contextualized embeddings between the reference and machine translated texts. It

		machine translation tasks.	is evaluated using equations (11) to (16)
RTF	1. Processing speed of target audio signal is needed	Speech-to-text	Computed using equation (17)
STOI	1. Speech intelligibility is needed.	Text-to-speech, speech-to-speech translation tasks	Computed using the steps highlighted in section 2.2.7
PESQ	1. Speech quality is needed	Text-to-speech, speech-to-speech translation tasks	Computed using the steps highlighted in section 2.2.8

IV. STATE OF THE ART (SOTA) SPEECH-TO-SPEECH MODELS' PERFORMANCE METRICS

The performance metrics utilised by some SOTA speech-to-speech translation models metrics utilised by researchers in this field are highlighted in Table 4. It shows that some researchers utilised the BLEU score along with MOS for speech-to-speech translation tasks. Some new metrics like the BLASER, XSTS, and ROUGE – L are beginning to be used by researchers in this area of research including speech-to-texts, and automatic speech-to-texts translation [27].

Table 4: Speech-to-Speech Translation Metrics Utilised for well-known SOTA models

Performance Metrics / Speech Models / Authors	BLEU scores	MOS Naturalness	MOS Similarities	Statistical Precision, Recall, f1-score	ROUGE-L / MCD / WER / BLASER	Others
Ref. [11]		MOS	MOS		WER	
Ref. [19]	BLEU score	Yes				
Ref. [20]	BLUE	MOS	MOS		WER	Latency
Ref. [28] - AudioPalm	ASR BLEU	Yes	Yes		WER	
Ref. [4] – Translatotron	BLEU score	Yes	Yes			Phoneme Error Rate (PER)
Ref. [29] - Translatotron2	BLEU score	Yes	Yes			
Ref [26] - Whisper	BLEU score		Yes			
Ref. [21]	BLEU score	MOS	MOS			
Ref. [27]	BLEU-4, Google BLEU			Yes	ROUGE-L	METEOR. BERTScore
Ref. [12, 30]	ASR BLEU	MOS Naturalness		ASR chrF		BLASER 2.0, XSTS, percentage acceptable translation, METEOR
Ref. [15]	BLEU score	Yes				

Ref. [31]	BLEU score					
Ref. [32]	BLEU score					Character Error Rate (CER)
Ref. [33]	ASR BLEU					
Ref. [34]	Units-BLEU, ASR BLEU	MOS	SMOS	ASR chrF	BLASER 2.0	Speaker Encoder Cosine Similarity (SECS)
Ref. [35]	BLEU					Character Error Rate (CER)
Ref. [36]	ASR BLEU					
Ref. [16]					WER, ROUGE-L	
Ref. [17]					WER	Word Recognition Rate (WRR), RTF
Ref. [8]	BLEU					
Ref. [37]					MCD	

V. APPLICATIONS OF SPEECH METRICS ON LEADERBOARDS AND MODERN AI APPLICATIONS

In this modern-day era, speech models are mostly compared with other models to know how they perform among themselves. Different models are evaluated or tested using the same dataset and ranked based on their performance. For instance, speech-to-speech translation models such as Whispers [26], Translatotron, SeamlessM4T may be benchmarked with same datasets of different varieties, across different databases such as FLUERS, LibriSpeech, MustC, Fisher datasets, and then the BLEU scores are computed for each model across these datasets and are ranked based on these metrics. When more than one source of datasets is utilized, the average across these sources is computed to rank each model.

At present, there are quite a few leaderboards and modern AI platforms [45-46] that evaluate and rank speech models such as the Hugging Face, International Workshop on Spoken Language Translation (IWSLT), Real-World Speech-to-Text API Leaderboard, Open ASR leaderboard etc [40-41, 42-43, 46-48]. Metrics such as BLEU scores, WER, METEORS, Real Time Factor (RTF), Short-Time Objective Intelligibility (STOI), Perceptual Evaluation of Speech Quality (PESQ), CER, are being utilized to evaluate and rank speech models. There is no known information about whether subjective metrics such as MOS Naturalness, MOS Similarity, BLASER, and MCD are being used on any of these platforms. BERTScore, METEOR, ROUGE-L, and BLEU scores are used on Hugging Face for texts generation models like texts summarization, and machine translation models. On the Open ASR Leaderboard on Hugging Face, ASR models are being compared and ranked, and metrics of choice are the WER, and Real Time Factor (RTF). Where the WER and RTF are utilized to evaluate the performance, the speech-to-texts models and are ranked based on these metrics. However, this review paper is suggesting the utilization of BERTScore for speech-to-speech translation models where it can be used on the transcribed texts of the target speech. Then the text is compared to the reference text by computing the cosine similarity between them. In such application, it is important to not rely on the BERTScore alone but to integrate it with other metrics such as the subjective evaluation metrics, and the BLEU score because the BERTScore cannot evaluate speech quality even though it evaluates the word order. Some metrics are peculiar to each leaderboard as well as speech models. For instance, on the Hugging Face leaderboard, A detailed overview of these leaderboards is given in the next sub section.

5.1 Hugging Face Leaderboard

Hugging Face leaderboard is an AI platform that evaluates the SOTA AI models such as the image processing models, text-based models, and speech processing models [42-43, 46-48, 50-51]. The platform evaluates and compares ASR models on its Open ASR Leaderboard [50]. ASR models are ranked using the WER, and RTF. TTS models are also being ranked via this platform [47-48, 51].

5.2 ICASSP 2024 Speech Signal Improvement Challenge

This is a speech models competing leaderboard that aims to improve speech signals by evaluating speech models for their speech signals quality and intelligibility. Speech signals are evaluated using techniques such as filtering, noise reduction, and speech enhancement. The metrics utilized here are Short Time Objective Intelligibility (STOI), and Perceptual Evaluation of Speech Quality (PESQ), Word Accuracy (WAcc) [65].

5.3 IberSPEECH 2024 Challenge

This platform was developed to promote research and development in speech processing applications such as speech synthesis, ASR etc. It looks into the evaluation of speech recognition and speech synthesis models. WER, and Character Error Rate (CER) are used to evaluate the ASR models while text-to-speech models are evaluated using PESQ, and STOI [64].

5.4 International Workshop on Spoken Language Translation (IWSLT)

This platform promotes research in Spoken Language Translation (SLT) such as speech-to-text, speech-to-speech translation, automatic speech translation, Speech synthesis etc., [40-41]. Speech-to-texts and speech-to-speech translation models are evaluated and ranked on this platform where BLEU scores, and METEOR are utilized to evaluate the ASR models, while speech-to-speech translation models are evaluated using BLEU scores, METEOR, and WER.

5.5 Speech Generation Evaluation and Leaderboard

This platform evaluates and ranks speech generation models using metrics such as speech intelligibility, which is measured by speech recognition error rates; Naturalness, which is predicted utilising speech models trained on human naturalness ratings; and Similarity, which measures the cosine similarity speaker embeddings mostly used for voice cloning systems [46, 49].

VI. TYPICAL LEADERBOARD RATINGS FOR DIRECT AND CASCADED SPEECH-TO-SPEECH TRANSLATION MODELS.

6.1 ASR BLEU Speech-to-Speech Translation on FLEURS X-ENG

For the ASR BLEU metric, the speech-to-speech translation tasks from other language to English on FLUERS corpus shows that GenTranslateV2, GenTranslateV1, SeamlessM4T LargeV2, SeamlessM4T Large, AudioPaLM2, WhisperV2, SeamlessM4T Medium have ASR BLEU scores of 32.3, 30.1, 29.4, 25.8, 24.0, 23.5, and 20.4 respectively, where the highest BLEU score of 32.3, was obtained for GenTranslateV2, with SeamlessM4T Medium having the lowest BLEU score. This leaderboard is available on this link: https://paperswithcode.com/sota/speech-to-speech-translation-on-fleurs-x-eng?utm_source=chatgpt.com. It should be noted that the authors of the GenTranslateV2 developed both end-to-end and cascaded system where the end-to-end models performed better than all the other models over 30 languages to English translation on both FLEURS X-Eng and CoVoST X-Eng datasets. For 15 languages to English on FLEURS X-Eng dataset, it achieved an average BLEU score of 32.3 while GenTranslateV1, SeamlessM4T LargeV2, SeamlessM4T Large, AudioPaLM2, and WhisperV2 have average BLEU scores of 30.1, 29.4, 27.1, 24.0, 23.5 respectively. For the cascaded system, GenTranslateV2, GenTranslateV1, SeamlessM4T V2, SeamlessM4T, and WhisperV2 have average BLEU scores of 34.2, 34.0, 32.3, 31.9, and 31.2 respectively. This shows GenTranslateV2 still performs better in the cascaded speech-to-speech translation task [52].

6.2 ASR BLEU For Speech-to-Speech Translation on CVSS dataset

On another rank, where both SeamlessM4T Large and SeamlessM4T Medium were ranked, results on the leaderboard shows that SeamlessM4T Large had the best ASR BLEU with a value of 36.5 in comparison with 28.1 for SeamlessM4T Medium when both were trained on CVSS Dataset. The link is available here: https://paperswithcode.com/sota/speech-to-speech-translation-on-cvsss

6.3 ASR WER Speech-to-Text Translation on Hugging Face Leaderboard

Using the 8 datasets used in the ESB paper [53], which consists of LibriSpeech clean, LibriSpeech other, VoxPopuli, TED-LIUM, GigaSpeech, SPGISpeech, Earnings-22, and AMI datasets as the benchmark datasets, Granite-speech-3.3-8b which was trained on public and synthetically generated datasets for ASR, and Automatic Speech Translation (AST) tasks achieved the best WER of 5.85 in comparison to Massively Multilingual Speech (MMS) - Finetuned ASR - FL102 with a wave2vec architecture which has the worst WER of 39.8. SOTA Whisper large, and Whisper medium have WERs of 7.94, and 8.09 respectively. Whisper-large-v3 has the best WER amongst all the Whisper models ranked with a value of 7.44. Facebook's Hubert-xlarge-ls960-ft has WER of 22.55. It should be noted that all models ranked on this leaderboard were trained with the same 8 training datasets aforementioned after which comparison were made. The average WER across all the 8 datasets were computed for each ASR model [54].

6.4 WER for ASR on TedLium Dataset

In another leaderboard for ASR WER on TedLium dataset (a dataset that contains English language TED Talks which spans from 118 to 452 hours sampled at 16 kHz with their respective transcripts), United-MedASR trained on 764 parameters, parakeet-rnnt-1.1b, Whispering-LLaMa-7b, and SpeechStew trained 100 M parameters yielded WERs of 0.29, 3.92, 4.6, and 5.3 respectively, which shows that United-MedASR has the best WER. This leaderboard is available at this link: https://paperswithcode.com/sota/speech-recognition-on-tedlium

VII. CASCADED & DIRECT SPEECH-TO-SPEECH PERFORMANCE METRICS

The conventional approach to speech-to-speech translation models before the exploration of machine / deep learning-based methods involves utilising cascading of traditional statistical approaches such as Hidden Markov Model (HMM), Forward Algorithms, Viterbi Algorithm etc. for ASR, statistical approaches such as HMM, analysis of transcribed words for machine translation and concatenative approach, rule-based approach, statistical approach for text-to-speech [4, 20, 55-56]. At a later time when AI is evolving, the machine learning based approach involving deep learning such as neural networks, LSTM etc., [20, 57-58] are being applied in this cascaded approach to modeling speech-to-speech translation task. Due to the availability of high computing power [61, 62], coupled with big data, deep learning based a direct end-to-end approach begins to take over the training of speech-to-speech translation model, where texts representation as seen in the cascaded approach is not available [4]. Of course, one, would expect that metrics of evaluation for the cascaded approach will involve integration of metrics for ASR, MT, and SS models, whereas the metrics of the direct approach involves a single metrics per time to evaluate target speech output. Table 5 highlights some of the metrics utilised for cascaded and direct speech-to-speech translation tasks.

Table 5. Summary of Cascaded and Direct Speech-to-Speech Translation Metrics

Performance Metrics Speech Models / Authors	Approach	Speech-to-Speech Metrics Used
Ref [1]	Direct	BLEU, METEOR
Ref. [19]	Cascaded (MT, speech synthesis, speech recognition)	MT- BLEU score, ChrF, CharBLEU, Speech synthesis - MOS Naturalness, MOS Similarity, MCD
Ref. [20]	Cascaded	Streaming ASR (WER), Simultaneous MT (BLEU score), Incremental Multi-lingual TTS (MOS Naturalness, MOS Similarity), Latency
Ref. [28] – AudioPalm	Direct	ASR BLEU, MOS Similarity, BLEU, WER
Ref. [4] – Translatotron	Direct, (compared with cascaded)	BLEU score, MOS Naturalness, Phoneme Error Rate (PER)
Ref. [29] - Translatotron2	Direct	BLEU score, MOS Naturalness, MOS Similarity
Ref [26] – Whisper	Direct / Self-supervised	BLEU score, MOS Similarity
Ref. [27]	Cascaded and Direct	BLEU-4, Google BLEU, MOS Similarity, ROUGE-L, METEOR. BERTScore, NIST
Ref. [12, 30] - Seamless M4T	Direct	ASR BLEU, MOS Naturalness), ASR chrF, BLASER 2.0, XSTS, percentage acceptable translation, METEOR
Ref. [15]	Cascaded	BLEU score, MOS Naturalness, MOS Similarity,
Ref. [31]	Direct (compared with cascaded)	BLEU score
Ref. [32]	Direct	BLEU score, Character Error Rate (CER)
Ref. [33]	Direct	ASR BLEU
Ref. [34]	Direct	Units-BLEU, ASR BLEU, MOS, SMOS, Speaker Encoder Cosine Similarity (SECS)
Ref [10]	Direct	ASR BLEU
Ref [6]	Cascaded (compared with Direct -Translatotron)	BLEU Scores, MOS Naturalness

VIII. DISCUSSION

The study highlights the various performance metrics utilised by researchers for speech processing applications, particularly speech-to-speech translation tasks. Based on the findings as reported in this work, most of the existing speech-to-speech translation models have utilised objective BLEU score performance metric for evaluation [7, 9, 15, 30-33]. MOS Naturalness, and MOS Similarity follow next as the performance metrics in this domain [12, 28-29, 34]. Other metrics that could be utilised for speech-to-speech translation tasks are METEOR, and ROUGE-L [1], [27]. Other metrics such as the WER, CER, NIST, XSTS, SER, PER, and BLASER are also of interest in this field of speech processing applications.

A thorough analysis of the various performance metrics utilised for speech-to-speech translation tasks show that all the subjective evaluations are computed on the generated output speech while that of the objective evaluation metrics show they are computed on the transcribed text string using a STT model except the MCD which is mostly utilised for TTS [35-37]. Hence, it is expected that the subjected evaluation metrics gives the best performance when compared to its objective counterpart due to no errors introduced as a result of the absence of ASR transformation [19]. Findings show that when it comes to adequacy which shows how close the predicted target output speech is to the source speech, MOS Similarity as well as XSTS, BLEU score, and ROUGE-L could be utilised to perform evaluation. MOS Naturalness can be utilised to check the naturalness of the output speech. For audio translation quality, the MOS Naturalness, BLASER, XSTS, as well as BLEU score could be utilised to achieve that [12]. The outcome of the study further suggests that ROUGE-L performance metric and its utilization in the NLP tasks such as machine translation and speech recognition [7], [27] should be given priority as an evaluation metric for speech-to-speech translation tasks. This is due to the fact that it is to be applied on the transcribed texts [1] obtained from the generated output target speech just like the case of the BLEU score metric. However, care must be taken due to its limitation of not being able to give good evaluations of two or more different translated texts that have same number of words (word-level) or characters (character-level) but different order - same ROUGE-L scores [9]. It is therefore advisable that it is integrated with other metrics such as BLEU, and METEOR. Coupled with that, ASR chrF is known to perform better than ASR BLEU due to its ability to perform more matching between the translated output texts and ground truth texts at the character level. WERs are mostly utilised for ASR models, but they can also be used for speech-to-speech translation tasks. MCD has little application for speech translation tasks. They are mostly utilised for speech synthesis from texts (TTS model) [36-38].

The study went further to survey some of the present leaderboards and modern AI tools available for evaluating and comparing speech models [44-45]. Some of the existing leaderboards such as Facebook's Hugging Face, IWSLT etc., [40-41, 42-43] evaluates speech models such as the TTS, and ASR. These evaluations give experts insight into how the speech models perform in comparison to one another. There are also leaderboards specifically for TTS and speech generations [49, 50] that compare TTS models with one another. The choice of metrics utilized in any of the leaderboards is dependent on the speech models being considered, as well as the leaderboards of interest. For instance, on Facebook's Open ASR leaderboards, the WER, and RTF are being used to compare and evaluate ASR models.

IX. CONCLUSION

The various metrics utilised for speech-to-speech translation models, their benefits and the comparison of the metrics were highlighted in this study. The results showed that among the various speech models metrics that have been employed, BLEU score is predominant, followed by MOS Naturalness and MOS Similarity. Metrics such as the BLASER, XSTS, ROUGE-L, BERTScores, and METEORS are beginning to gain recognition particularly for speech models. Leaderboards ratings of speech models show that existing BLEU scores, WER, and RTF are mostly utilized for speech models. This further suggests the importance of these metrics. RTF even though it is being utilized on the leaderboards, has the least utilization by researchers. Also, metrics such as ROUGE-L, METEORS, and BERTScore have been utilised successfully in machine translation, they could be explored for speech-to-speech translation particularly when they are used in conjunction with each other coupled with BLEU score. The findings show that the subjective metrics are computed directly on the target speech output, which depicts a good evaluation of the quality of speech model, unlike the objective metrics that are prone to errors introduced due to the ASR utilization. The study therefore serves as an eye opener to researchers or readers hoping to develop speech-to-speech translation models to make the right choices on the performance metrics of their models.

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